

**MANAGEMENT OF BLOWDOWN FROM CLOSED LOOP COOLING
SYSTEMS USING IMPAIRED WATERS**

by

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University of Pittsburgh, 2010

Management of cooling tower blowdown is one of the key components in cooling tower operation and usually requires treatment to meet local, state or federal discharge regulations. Typical options for power plants blowdown management include discharge to surface waters or wastewater treatment plants (WWTPs) and zero liquid discharge (ZLD). Compared to other options, ZLD is preferred as it helps to decrease environmental impact of power generation, especially for power plants using reclaimed water for their recirculating cooling systems. ZLD typically includes one or more of the following advanced treatment technologies: (1) Membrane filtration; (2) Electrodialysis (ED); and (3) Evaporation.

The objectives of cooling tower blowdown treatment is to recover water with the quality equal to or better than the makeup water so that it can be returned to the cooling loop. In this study, membrane filtration was evaluated as a possible treatment option for blowdown from cooling towers operated using secondary treated municipal wastewater (“MWW blowdown”) and acid mine drainage (“AMD blowdown”) as make up water.

Treatability studies with microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) membranes, were carried out for the MWW and AMD blowdown in a bench-scale membrane filtration unit. It was observed that the nanofiltration with BW30 membrane was effective in reducing the concentration of dissolved species in MWW blowdown: TDS and sulfate decreased from 3,060 and 326 mg/L to 379 and 31 mg/L, respectively.

Sequential filtration by NF90 and BW30 membranes was required to reduce the TDS and sulfate in AMD blowdown from 5,810 and 3,079 mg/L to 192 and 107 mg/L, respectively. Preliminary studies also indicated that a trans-membrane pressure of 135 psi is sufficient to achieve acceptable permeate flux. Lowering pH of the feed water from 7.4 to 6.0 resulted in higher permeate flux, while increasing it to 9.0 had an adverse impact on permeate flux.

Laboratory tests performed in this study indicate that nanofiltration could be a viable alternative for the treatment of blowdown from cooling tower systems using impaired waters (i.e., secondary treated municipal wastewater or passively treated acid mine drainage).

KEY WORDS: Zero liquid discharge, Municipal wastewater, Acid mine drainage, Microfiltration, Ultrafiltration, Nanofiltration, Reverse osmosis, Transmembrane Pressure.

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1.0 INTRODUCTION

Cooling tower operation includes periodic discharge of concentrated recirculating water in order to maintain desired cycles of concentration and control the buildup of solids in the system resulting from continuous influx of solids with makeup water and evaporative losses in the system (Figure 1). This periodic discharge of recirculating water is called blowdown and it contains elevated levels of solids as well as chemicals that are typically added to the system to control corrosion, scaling and biofouling. Due to fairly low water quality, blowdown is typically subjected to some level of treatment in order to meet discharge requirements that are governed by the final disposal options. The primary objective of blowdown management is to treat blowdown to attain quality that is equal to or better than the makeup water so that it can be reused as makeup water. Alternatively, blowdown may be subjected to different treatment processes to meet discharge requirements or to minimize its volume for easier disposal.

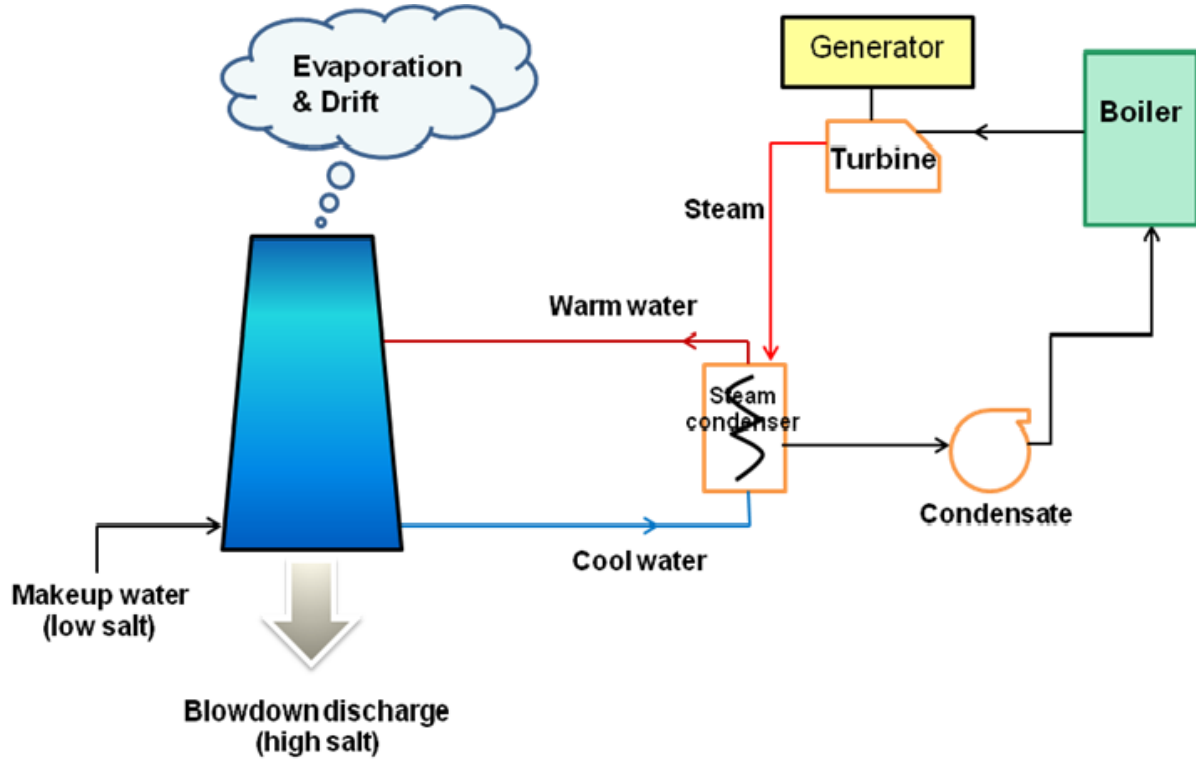


Figure 1. Schematic of a recirculating cooling water system in a coal-fired power plant.

2.0 BLOWDOWN MANAGEMENT OPTIONS

Management options available for cooling tower blowdown typically depend on its water quality, local discharge regulations and capabilities of treatment processes under consideration.

Typical options for power plant blowdown management include:

- Discharge to surface waters. This is the main option for once-through cooling systems that is not feasible for recirculating cooling systems because of the blowdown quality.

- Discharge to wastewater treatment plants (WWTPs): This is probably the most cost effective management alternative but may not be feasible for many plants since the WWTP may not accept the blowdown without any pre-treatment due to extremely high solids and presence of other chemicals in the blowdown that were added to control corrosion, scaling and biofouling.

- Zero liquid discharge (ZLD): This alternative involves extensive treatment of blowdown to facilitate its reuse combined with some form of volume reduction to minimize or eliminate the need for liquid discharge. As seen in Table 1, most power plants using wastewater for cooling would choose this option where the concentrated solids are the only waste leaving the plant.

Table 1. Treatment technologies and types of discharge of blowdown from power plants using reclaimed waters.

Plant Name	State	Type of discharge	Treatment technologies
Magnolia	CA	ZLD	Lime-soda softening, media filtration, RO, evaporator, evaporation pond
Emery	IA	WWTP	
Panda Brandywine	MD	WWTP	
Jones Station	TX	ZLD, irrigation	Evaporation pond
San Juan	NM	ZLD	Evaporator, evaporation pond, RO
Linden	NJ	WWTP	
Nixon	CO	ZLD	RO, evaporator
MVPP	CA	WWTP, recycle	RO
Palo Verde	AZ	ZLD	Evaporation pond
Walnut Creek Energy Park	CA	WWTP	

Notes: ZLD: zero liquid discharge.

WWTP: discharge to wastewater treatment plants or sanitary sewer system.

2.1 DIRECT DISCHARGE TO SURFACE WATERS

Federal, state and local regulations govern the discharge requirements for cooling system blowdown. If allowed, direct discharge of blowdown to surface water or ground water would be a simple and economical choice. However, the assimilative capacity of receiving water to handle the blowdown is limited and the quality of blowdown has to meet criteria that address the regulatory requirements for public health and environmental protection. Considering the cooling tower blowdown quality, discharge to surface water is only feasible for once-through cooling systems.

At federal level, Clean Water Act (CWA) Section 402 established the National Pollutant Discharge Elimination System (NPDES), which requires that all point-source discharges of pollutant to surface waters must be authorized by an NPDES permit. General NPDES permits can be water quality based or technology based. The water quality limitations, which are mainly concerned with the concentrations of toxic chemicals, depend on the quality of the receiving stream and its assimilative capacity. For each point source with NPDES permit, its water quality is calculated, monitored, and regulated based on the surface water quality limitation. Based on different technologies implemented in cooling tower design and operation, the concentrations of available chlorine, chromium, and zinc are likely to be the confining factors. Otherwise, the effluent guidelines title 40, part 423 of Code of Federal Regulations (40 CFR 423) specifying a 30-30 rule for both TSS and BOD (30 mg/L each) with a maximum concentration of 100 mg/L for TSS and are applicable to cooling tower blowdown as a categorical waste. However, site specific evaluation is usually needed for a given point discharge.

The state regulations or guidelines often include restrictions that limit the level of bacteria in blowdown (i.e., fecal or total coliforms). Furthermore, certain chemical constituents may also be a concern when present in excessive quantities. For example, in April 2009, Pennsylvania DEP released a “Permitting Strategy for High Total Dissolved Solids (TDS) Wastewater Discharges” which specifies 500 mg/L (max 750 mg/L) for TDS and 250 milligrams per liter for chlorides and sulfates, if the discharge is located in the Monongahela River watershed.

In summary, each cooling tower is subjected to different local regulations based on the blowdown characteristics and intended discharge alternative and there is no unifying standard for cooling tower blowdown discharge, especially when impaired waters are used as makeup water.

2.2 DISCHARGE TO WASTEWATER TREATMENT PLANTS

Blowdown discharge to a local wastewater treatment plant (WWTP) may be an attractive and economical option if accepted by the WWTP. The acceptance may be contingent on chemicals present in the blowdown, especially for the power plants that do not include tertiary treatment, because of the potential to compromise its own NPDES permit. Blowdown discharge to a WWTP reduces the burden on power plants but increases the demand on local WWTPs. The size and treatment options are the two key factors that determine whether a WWTP can accept the cooling tower blowdown from a thermoelectric power plant.

Table 2 provides chemical composition of blowdown samples that were collected from pilot-scale cooling towers operated with two different impaired waters: treated acid mine drainage (AMD) and secondary municipal wastewater (MWW). The data in Table 2 indicate that high TDS in blowdown from towers operated with AMD and those operated with MWW as well as high sulfate concentration in the towers operated with AMD are the main characteristics of concern.

Usual secondary treatment in WWTPs (Figure 2) includes biological treatment step in the aeration tank, which is the key step in treating organic compounds in municipal wastewaters. If the TDS in the feed water is too high, it will adversely impact microbial activity in the aeration

tank and reduce the overall treatment efficiency of the WWTP. Therefore, every WWTP has pre-treatment requirements for each industrial contributor and will only accept the blowdown from a thermoelectric power plant if it will not compromise its treatment efficiency.

Table 2. Chemical composition of the blowdown waters from pilot-scale cooling towers
(all units are in mg/L unless specified otherwise).

Constituent	AMD	MWW
Ca	800	140
Mg	238	50
Na	446	700
K	29	60
Al	ND	0.2
Cu	ND	0.2
Fe	ND	0.5
Mn	0.2	0.4
Zn	ND	0.2
Cl	216	1030
SO ₄	2930	300
SiO ₂	59	25
NO ₃ -N	1.1	16
NH ₃ -N	0.6	2.2
PO ₄	0.6	15
Total Alk. (as CaCO ₃)	407	301
HCO ₃ Alk. (as CaCO ₃)	276	189
BOD	ND	72
TOC	13.8	120
TDS	5160	2580
TSS	11.7	95.7
Turbidity (NTU)	12	55
Conductance (mS/cm)	6.3	4.8
pH (no unit)	8.9	8.5

Notes:

ND: not detected.

Both blowdown waters were collected from pilot-scale cooling towers, whose water treatment recipe for corrosion, scaling, and biofouling control is available in previous sections of this reports.

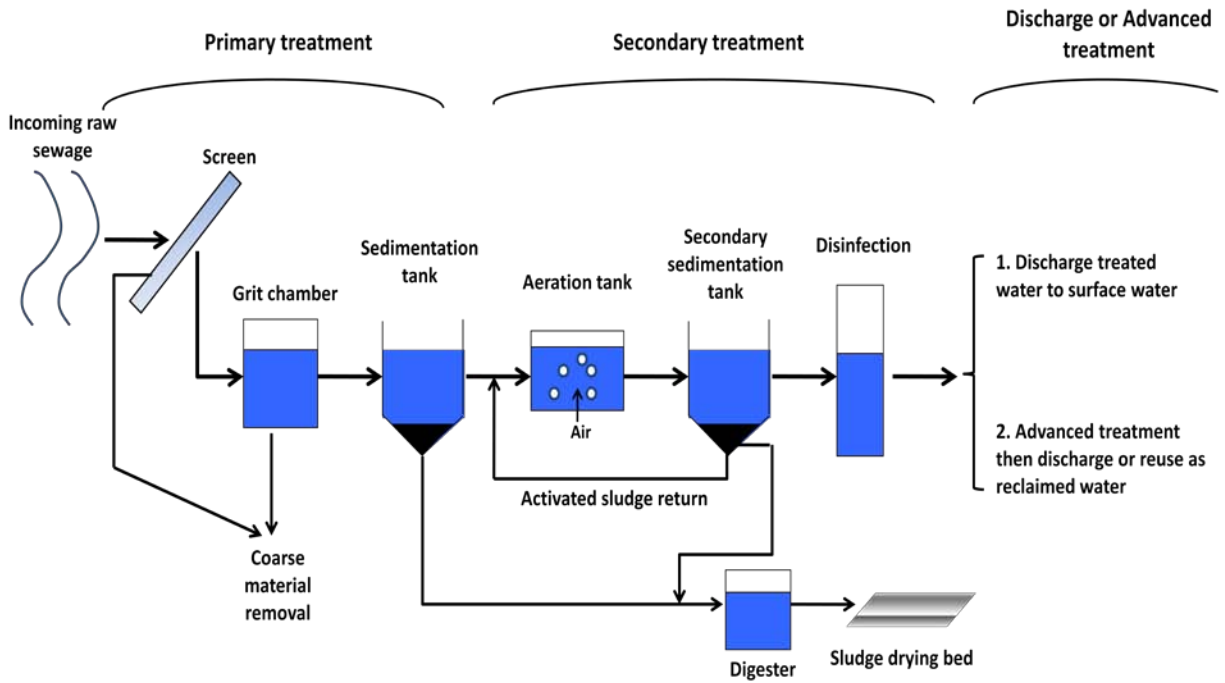


Figure 2. Typical wastewater treatment processes in WWTPs.

Case study of a power plant discharging to WWTP

Panda Brandywine power plant

Panda Brandywine power plant (PBPP), which is operated by Panda Global Services, is an example of a power plant that uses municipal wastewater as makeup water and discharges its blowdown back to the wastewater treatment plant. PBPP is located in Brandywine, Prince George's County, Maryland, about 15 miles southeast of Washington, DC. PBPP began its operating in October 1996 with a capacity of 230 MW (Veil, 2007). It is a natural gas-fired combined-cycle plant with two 84 MW combustion turbines, two heat recovery steam generators

and one 80 MW Steam turbine. The plant uses about 1.5 MGD of tertiary-treated water from the Washington Suburban Sanitary Commission (WSSC) Mattawoman Wastewater Treatment Plant which has a design capacity of 15 MGD. The Reclaimed municipal wastewater, which travels through an 18-mile pipeline to the PBPP (in Figure 3), has been used at the Panda plant since 1997 and comprises more than 95% of the total cooling water. Additional makeup water comes from a local groundwater source.

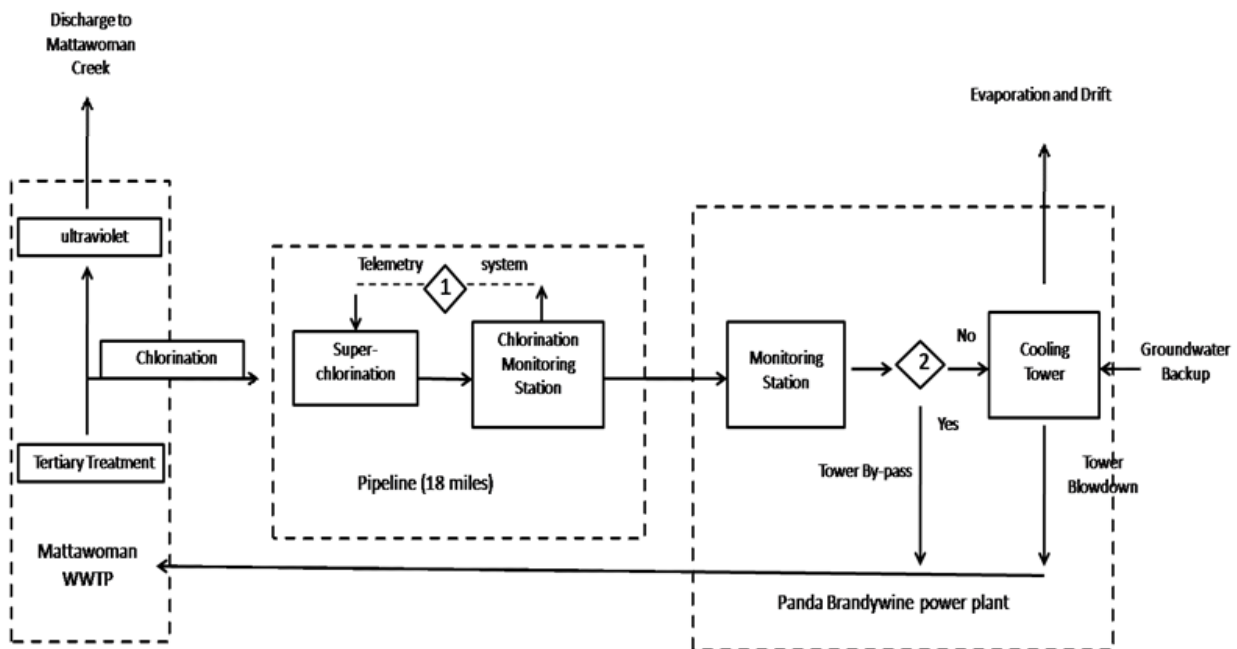


Figure 3. Panda Brandywine power plant systems.

Until recently, Mattawoman WWTP chlorinated the wastewater for disinfection, then dechlorinated prior to discharge through its NPDES outfall. However, Mattawoman switched to ultraviolet as its main method of disinfection. The plant still chlorinates the side stream of water that enters the reclaimed water pipeline. Prior to the switch to UV disinfection, the water sent to PBPP was withdrawn prior to dechlorination, so that chlorine residual could be maintained in the pipeline. When the reclaimed water reaches PBPP, it is chlorinated again using liquid sodium hypochlorite before it is used in the cooling systems. Panda Brandywine also adds other chemicals (e.g., corrosion inhibitors) for process control that would be added regardless of the source of cooling water.

Recirculating cooling water is removed as blowdown after 7 cycles of concentration and piped back to the Mattawoman treatment plant along with other sewage originating at the plant. The average blowdown flowrate is 10% on a continuous basis.

2.3 ZERO LIQUID DISCHARGE

Given the option, most power plants using reclaimed water for their recirculating cooling systems would choose zero liquid discharge (ZLD) as the main blowdown management option. The main reasons are high solids concentration and presence of specific chemicals added to

control corrosion, scaling and biofouling, which are usually not allowed to be discharged directly. Zero liquid discharge means that blowdown is treated and used internally in power plant. Internal use alternatives include cooling tower makeup or other systems, such as flue gas desulfurization or ash sluice, which need lower quality water. Compared to other discharge options, ZLD is preferred as it helps to decrease environmental impacts of power generation. ZLD typically includes one or more of the following advanced treatment technologies: (1) Reverse osmosis (RO); (2) Electrodialysis (ED); and (3) Evaporation.

2.3.1 Reverse Osmosis

Osmosis is defined as the spontaneous passage of a liquid through a semi-permeable membrane from a dilute to a more concentrated solution (Leonard & Richard, 1986). By applying pressure to the concentrated stream, the direction of flow can be reversed. In the reverse osmosis (RO) membrane treatment process, water is forced through a semi-permeable membrane that allows the passage of water molecules but prevents the passage of most dissolved solids. As a result, the permeate stream contains purified water while the concentrated waste brine is retained on the feed side.

In RO process, pressures of 350~600 psi are commonly used to achieve the desired separation. Among many inorganic and synthetic organic materials that possess the can retain

dissolved solids, cellulose acetate and polyamide are the most common membrane materials employed (Zeien and York, 1980). There are two types of commercial RO membrane configurations: hollow fiber and spiral wound. Hollow fiber membranes are not normally used in wastewater applications due to greater susceptibility to fouling. Spiral wound configuration is generally used for both industrial and utility wastewater applications. Large-scale industrial reverse osmosis systems usually consist of a large number of membrane modules, each of which contains several spiral wound elements. A typical RO module is illustrated in Figure 4, while Figure 5 depicts a typical reverse osmosis system consisting of several modules. In each spiral wound element, two membrane separated by a support are sealed together and attached to a perforated tube, which receives the permeate. A feed-side spacer is placed between the membranes and the two are rolled together around the tube. Brine flows across the membrane surface, while the permeate flows between the sealed membranes toward the perforated tube. As shown in Figure 4, a series of coupled elements are installed in an outer pressure vessel, with provision made for feed entry and for the removal of permeate and concentrate streams (Holiday, 1982).

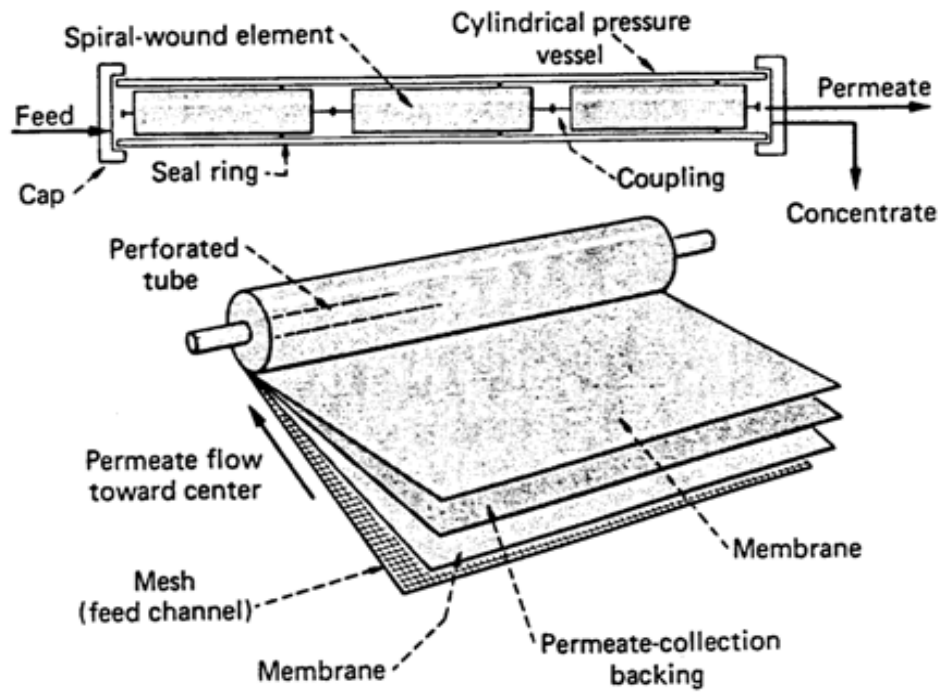


Figure 4. Typical reverse osmosis module containing three spiral-wound elements. (Holiday, 1982)

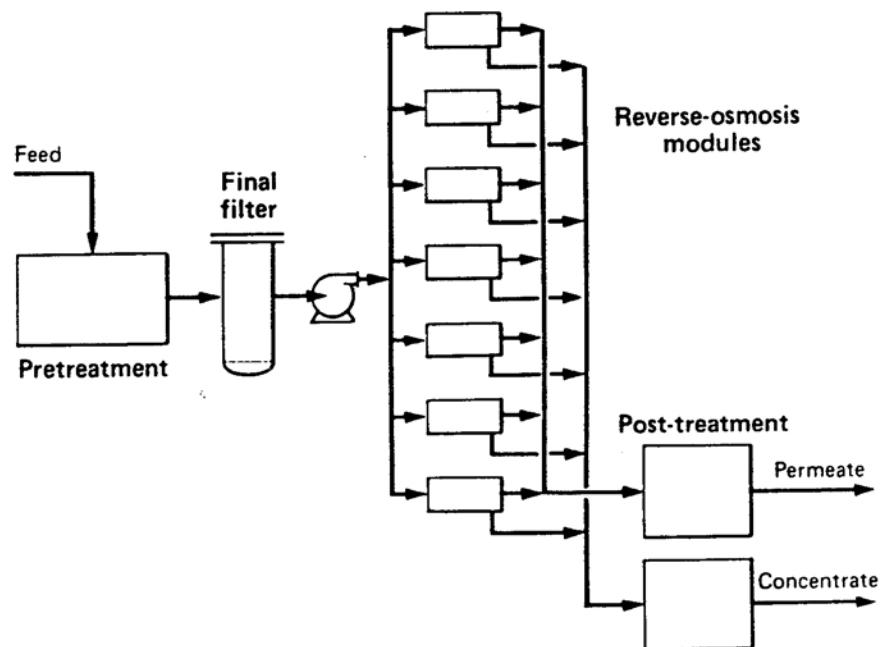


Figure 5. Typical reverse osmosis system containing several modules. (Holiday, 1982)

In order to reduce the hardness, metals and suspended solids in the feed water to prevent scaling and fouling of the membranes, extensive wastewater pretreatment is usually required ahead of RO membranes, especially when the water feed quality is not very good. The pretreatment systems usually include processes like chemical softening, media filtration and ion exchange. While the principal use of RO is to separate inorganic salts and minerals from water, the membrane can also be effective in removing organic pollutants.

During the past few decades, reverse osmosis systems have gained widespread applications in a variety of industrial utilities, such as desalination of salt and brackish water, treatment of municipal wastewater effluent and certain types of industrial wastewater treatment. Table 1 lists three power plants which employ RO unit to treat cooling tower blowdown and achieve zero liquid discharge. The use of RO system in San Juan Generating Station will be described in detail at the end of this section.

2.3.2 Electrodialysis

Similar to reverse osmosis systems, electrodialysis (ED) also uses semi-permeable membranes to separate a liquid solution into purified product and concentrated waste streams. However, in the case of ED, a direct current is used to drive ionic species through the membranes in contrast to the hydraulic pressure that is used in reverse osmosis systems. The ED process usually utilizes

separate anion and cation ion-exchange membranes; these membranes are very similar in composition to ion-exchange resins used in softening and demineralization. A schematic illustration of a typical ED system is shown in Figure 6, where the anion and cation membranes are labeled “A” and “C”. The anion and cation membranes are placed in an alternating stacked array and the electrodes are located at the two ends of the stack (Holiday, 1982).

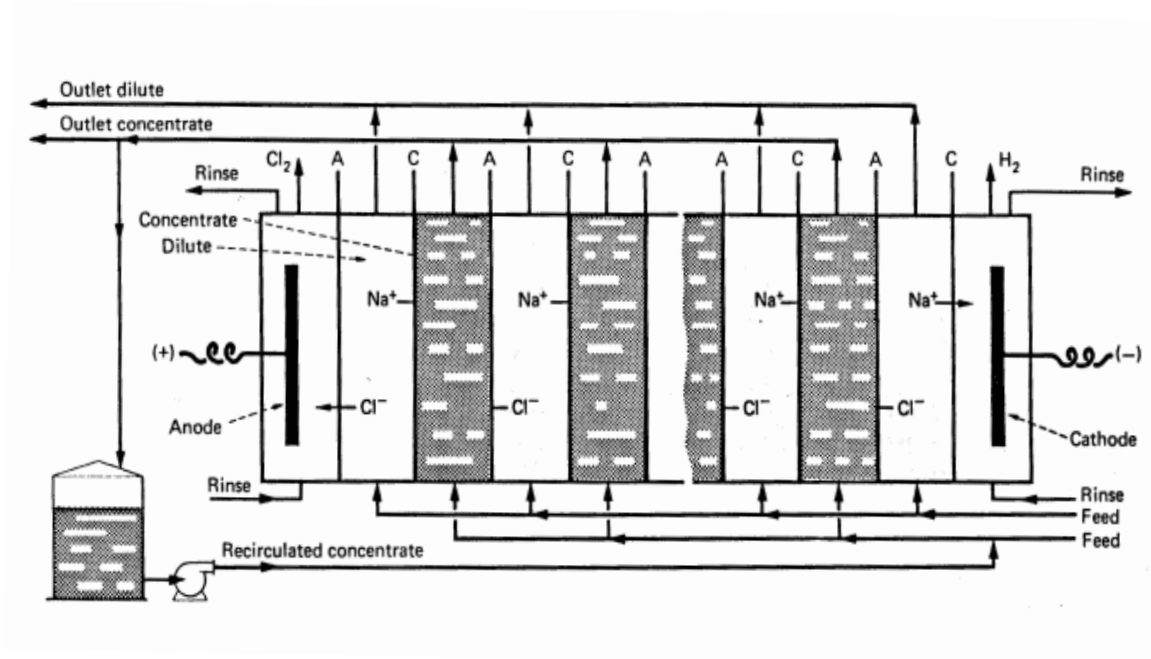


Figure 6. Schematic illustration of a typical electrodialysis system. (Holiday, 1982)

The influence of the imposed electrical potential causes the cations and anions to move in the opposite directions. The cations easily move through the cation membrane into the

concentration chamber, but are not able to pass through the anion exchange membrane and are retained in a concentrate stream. The anions are driven toward the anode and are also trapped in the concentration chamber. The feed stream enters the bottom of the unit and is directed via a manifold to multiple compartments. As the stream passes through each compartment, a portion of the salt is transferred through the membranes by the applied electrical potential gradient and the alternative chambers, into which the salt is transported, contain more concentrated stream. The inlet and output manifolds keep the diluted and concentrated streams separated (Zeien, 1980).

Electrodialysis systems are limited to removing ionic species from wastewaters and are unable to remove organic contaminants or other scalable compounds, such as silica. In addition, membrane scaling and fouling have long hampered ED for water treatment as they require extensive pretreatment to protect the membranes. In some cases, as shown in Figure 6, the diluted and concentrated streams are recirculated to keep flow velocity high enough to reduce scale formations. In fact, a modified electrodialysis system called “electrodialysis reversal (EDR)” has been developed to mitigate the scaling and fouling problems. In EDR process, a membrane cleaning action is influenced by periodic reversal of the DC polarity applied to the cell, which is made possible by the symmetric configuration of the cell. This cleaning action is comparable to the backflushing of filters. The polarity reversal makes the system more tolerant to scaling and fouling contaminants and reduces pretreatment requirements compared to traditional ED systems (Strauss, 1985).

Electrodialysis technology has been widely used in many municipal and industrial applications, including desalination of salt and brackish water, recovery of salt by concentration of sea water or recovery of metals from plating wastes, as well as roughing demineralizers for boiler feedwater upstream of ion exchange demineralizers (Strauss, 1985).

Electrodialysis system has been tested for the treatment of cooling tower blowdown (Ostanowski, 1984). Two pilot-scale tests were conducted in the U.S and South Africa

separately. At Etiwanda Station in Etiwanda, CA, a nine-month pilot study was conducted to test a conventional eletrodialysis system to treat the cooling tower blowdown which had been pretreated by softening, clarification and filtration. Another pilot test in South Africa was conducted at Grootvle Power Station with an EDR system, which also required a pretreatment process consisting of softening, recarbonation, filtration, chlorination and activated carbon. Based on the results of these two pilot studies, the first full-scale eletrodialysis system was commissioned for a 3,600 MW power station in the following year.

2.3.3 Evaporation

Evaporators or evaporation ponds are used as another technology to achieve ZLD. Evaporation is a natural process of transforming water in liquid form to water vapor in the air, which depends on local humidity, temperature, and wind conditions. Drier climates generally favor evaporation as a waste management technique. The simplest approach to evaporation involves placing produced wastewater in a pond, pit, or lagoon with a large surface area (Figure 7). Water can be left to passively evaporate from the surface as long as evaporation rate exceeds inflow rate. Evaporation is used to remove water from the cooling tower blowdown in many power plants, such as Magnolia in CA, Jones Station in TX or San Juan in NM.



Figure 7. Evaporation ponds. (*Source: BC Technologies Ltd.*)

Evaporation rates depend on the size and depth of the pond and influent characteristics. For example, in semiarid regions, hot, dry air moving from a land surface will result in higher evaporation rates for smaller ponds. The evaporation rate of a solution will decrease with an increase in ionic strength. Blowdown can be managed at small onsite evaporation ponds or can be sent offsite to commercial facilities that employ large evaporation basins. One potential problem with evaporation ponds stems from their attractiveness to migratory waterfowl. If evaporation ponds contain oil or other hydrocarbons on the surface, birds landing in the ponds could become coated with oil. Covering the ponds with netting helps to avoid this problem.

Somewhat different from evaporation ponds, evaporators use different technologies to increase rate of the liquid vaporization and overcomes the limits of natural conditions. Vapor recompression evaporators sometimes referred as “brine concentrators” represent a proven technology whose performance and reliability have been demonstrated at several power plants (Leonard & Richard, 1986). However, the capital and operating costs of evaporators are relatively high.

A vapor recompression evaporator is typically a long, tubular, vertical, falling film system that uses a vapor compression cycle. A schematic illustration of a typical vapor recompression evaporation system is shown in Figure 8. The pH of the wastewater is adjusted to between 5.5 and 6.5 by the addition of sulfuric acid. This acidified stream is pumped through a heat exchanger to recover the sensible heat from the distillable fraction before being fed into a deaerator to strip noncondensable gases, including carbon dioxide, oxygen and nitrogen from the water and vent them to the atmosphere. After the deaerator, water enters the primary feed heater, where its temperature is raised close to boiling by recovering sensible heat contained in the hot product water. The waste feed then enters the evaporator sump, where it is mixed with a concentrated slurry and recirculated to the top of the evaporator. It then falls in a thin film along the inside walls of the evaporator tubes. As the waste falls, it is partially converted to steam, which is then compressed and used as a heating medium on the shell side of the evaporator.

When the steam is compressed, its saturation temperature is increased, thus making its sensible heat available at a higher temperature level. The major energy requirement is the electrical power used to compress the steam. The steam exiting from the shell side is condensed. The condensate is pumped through the feed heater and recovered as product water.

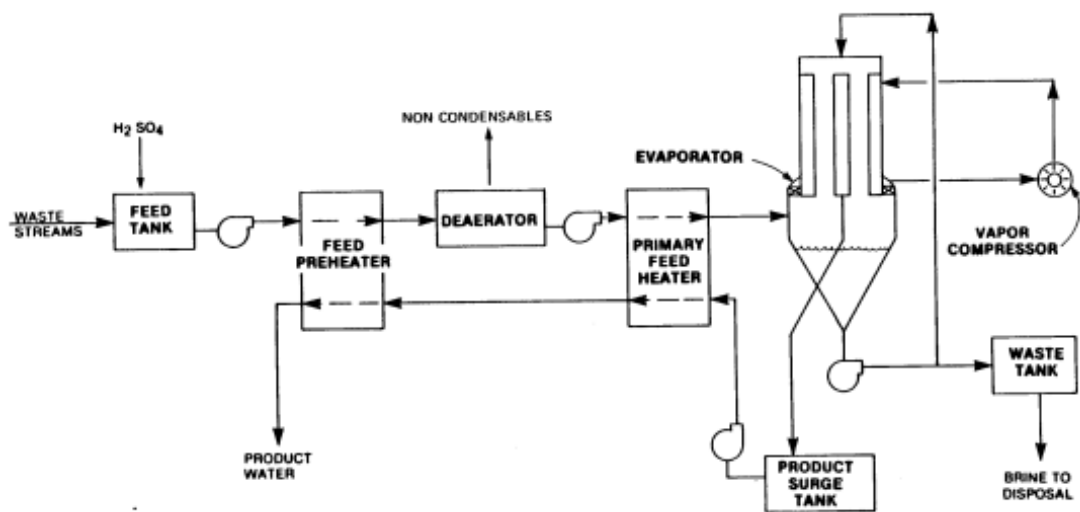


Figure 8. Schematic illustration of a typical vapor compression evaporation process. (Zeien, 1980)

Demisters are used to prevent entrainment and carryover from contaminating the purified water, which is usually of high enough quality to be used as boiler feedwater. Excess product water not needed for the boiler can be used as cooling tower makeup, which permits the cycles of concentration to be increased because of the purity of the makeup (Zeien, 1980; Pasricha, 1980).

Scale formation on the evaporator tubes can be problematic. To avoid this problem, calcium sulfate crystals can be added into the feed solution to induce preferential precipitation of scale-forming compounds on the crystals. The use of the seed slurry process permits a high concentration ratio while preventing scaling of the evaporator tubes (Leonard & Richard, 1986). Normally, 95-98% of the feed can be recovered as high quality distillate. The small volume that remains as concentrated brine and slurry can be disposed of in evaporation ponds or spray drier, depending on the net evaporation rate and other site-specific factors, such as land availability and cost.

An alternative to vapor recompression evaporators is offered by the “vertical tube foaming evaporators (VTFE)”. The principal differences between the VTFE system and vapor recompression evaporators include: (1) the VTFE one uses turbine exhaust steam as the source of heat for evaporation to reduce energy cost; (2) a surfactant is added to create a foamy flow on the tubes (Leonard & Richard, 1986). In principle, the use of the surfactants is expected to reduce the rate of scaling formation, lower hydrostatic losses and enhance the heat transfer efficiency in the evaporator (Paul, 1986). However, a potential problem of the VTFE system involves the direct coupling of the power generating cycle and the evaporator due to the use of the turbine exhaust steam because of the possible impact of evaporator problems on the availability of the power cycle.

Case study of a power plant using ZLD

San Juan Generating Station (SJGS)

The San Juan Generating Station (SJGS) is located in the northwest plateau of New Mexico, about 20 miles west of Farmington (Leonard & Richard, 1986). It is a semi-arid region with an average annual precipitation of approximately eight inches and minimal ground water supply. Water for the station is supplied entirely from the San Juan River, which is located about 10 miles south of the plant as one of the tributaries of the Colorado River.

In addition to the river water, the station also uses reclaimed water as cooling tower makeup water and receives it by pipeline. The reclaimed water originates as mine drainage from another part of their facility about one mile from the plant. Although the reclaimed water comprises less than 1% percent of the total 15000 gpm makeup flow, it is important to include it in consideration since San Juan Generating Station is a zero liquid discharge facility.

SJGS consists of four coal-fired units with a total generating capacity of 1800 MW. The water flow diagram for the entire site is shown in Figure 9. As one of the early pioneers in the use of sophisticated water recycling systems at power plants, the San Juan Generating Station went through continuous development during the 1980's and improved its processes in wastewater treatment to comply with ZLD requirements. The principal water recycling and conservation system employs five evaporators and four reverse osmosis units. The evaporators

are the vertical tube foaming evaporators (VTFEs) and a calcium sulfate as the surfactant is used to control scale formation. The main improvements involved the addition of lime-soda ash softening equipment, neutralization tanks and clarifiers upstream of the RO units and an additional brine concentrator with a capacity of 350 gpm. In fact, each one of four RO systems has a capacity of 500 gpm of wastewater and recovers 400 gpm of the high quality permeate. Each RO unit consist of spiral-wound acetate module configured in a two-pass array with 15 pressure vessels in the first pass and 9 pressure vessels in the second one.

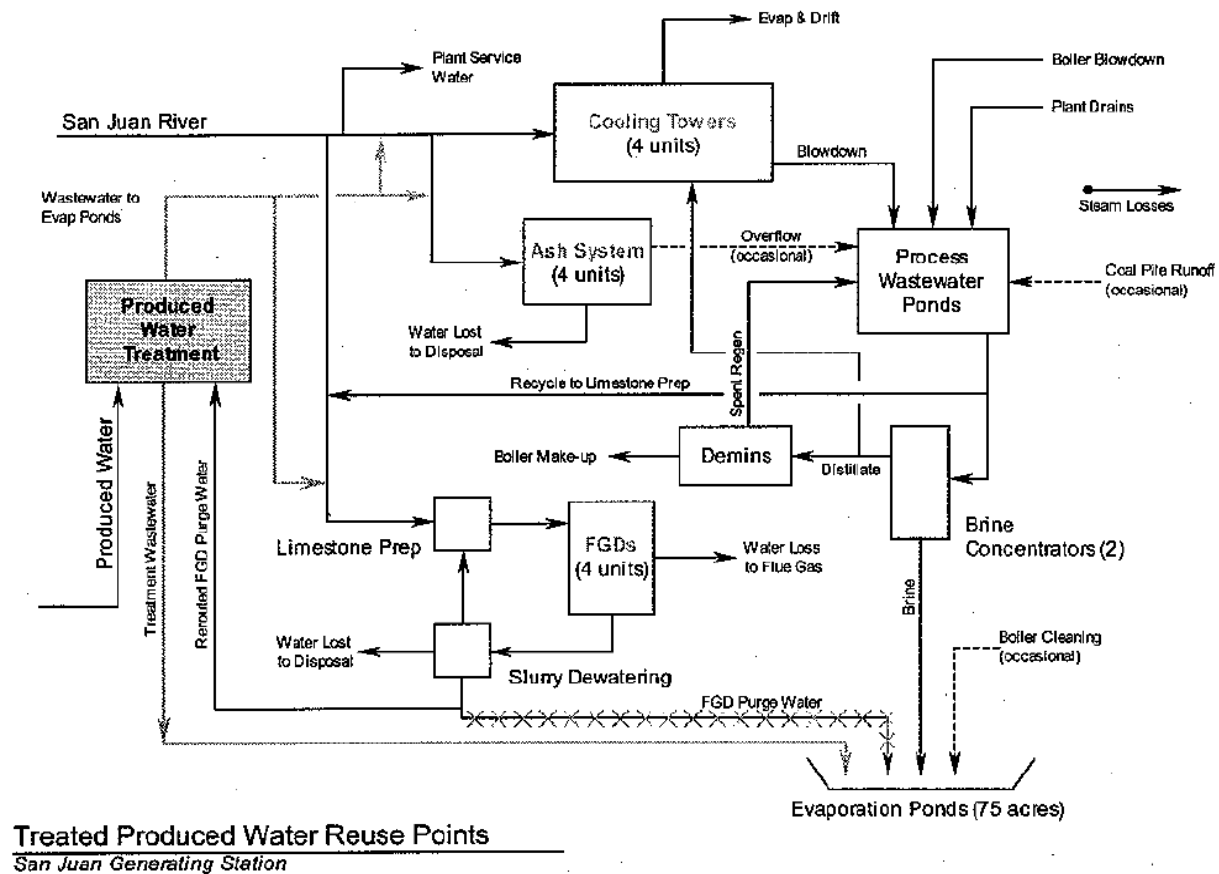


Figure 9. San Juan Generating Station. (Source: PNM Company. "San Juan Generating Station.")

At the SJGS, conventional recirculating wet cooling towers are employed. Since they are using high quality feed water as makeup, the towers in SJGS is being operated at 12 cycles of concentration and use standard cooling water treatment methods. A phosphonate-type inhibitor is continuously added to permit operation at concentrations above the solubility of calcium sulfate. Sulfuric acid is added to maintain the pH of the recirculating water between 7.9 and 8.3 to prevent calcium carbonate scaling. The towers are shock-treated for 1 hour twice a day with chlorine to prevent biofouling. The cooling towers are also equipped with drift eliminators to prevent water loss from the cooling towers and maintain the total particulate emissions limit for the entire plant.

The operation of the feed water pretreatment system and the RO/evaporator system produces both liquid and solid wastes. The average blowdown flowrate in the SJGS cooling system is around 800 GPM. The concentrated waste brine from the vapor recompression evaporators is pumped to evaporation ponds with a total surface area of 75 acres while the recovered water is sent back to the plant to be used as boiler makeup water. Solids from the clarifiers and evaporators are dewatered in centrifuges and disposed of in a polyethylene-lined sludge pit (Paul, 1984).

3.0 BLOWDOWN TREATMENT ALTERNATIVES

When the cooling tower blowdown cannot be discharged back to a WWTP or discharged directly to receiving waters, the blowdown needs to be treated. The treatment objective is to recover portion of the blowdown that will have the quality equal to or better than the makeup water so that it can be returned to the cooling loop to achieve ZLD operation. Specific treatment approaches depend largely on the characteristics of the blowdown water, which in turn depend on makeup water sources and cooling tower operating conditions (e.g., cycles of concentration).

Since neither TDS nor sulfate is effectively reduced by lime-soda ash softening/precipitation process which had been discussed in section 2.4, the feasibility of membrane filtration in reducing both TDS and sulfate was experimentally tested in the following. The treatment needs for the blowdown from the pilot-scale cooling towers operated with secondary treated municipal wastewater (“MWW blowdown”) and acid mine drainage (“AMD blowdown”) were independently assessed and analyzed.

Treatability studies with various types of membranes were carried out for the MWW and AMD blowdown water employing a bench-scale membrane filtration unit. Varieties of operating

parameters, including membrane types, trans-membrane pressure (TMP), and feed water pH, were tested for optimal treatment performance in terms of filtration flux and water quality improvement.

3.1 MEMBRANE FILTRATION

Membrane filtration experiments were conducted to evaluate the feasibility of using microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) or Reverse Osmosis (RO) in cooling tower blowdown water treatment.

Membranes are defined as barriers, which can separate two phases and restrict transport of various chemicals in a selective manner (Figure 10). As a result of increasingly stringent discharge standards, the use of membrane technology in wastewater treatment is growing rapidly. The wastewater, referred to as the feed, is driven through a membrane by an applied driving force. The fraction of the feed fluid that passes through the membrane is called the “permeate” and the fraction that is retained by the membrane is called the “retentate”. The driving force for separation can be pressure, concentration, electrical potential or a thermal force. The most common driving force and the one used in this study is pressure.

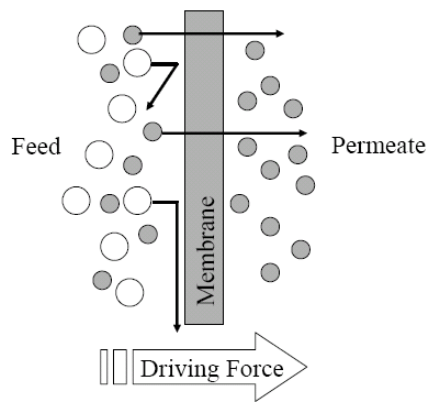


Figure 10. Membrane separation. (Bendick, 2003)

The various membrane processes are categorized by the size of the particles that are able to pass through the membrane. Membrane processes are classified as microfiltration, ultrafiltration, nanofiltration and reverse osmosis. Table 3 shows differences in size exclusion, typical operating pressures, and types of particles that are rejected for each membrane classification. The selection of NF membranes for blowdown treatment may be the most appropriate due to their ability to reject salts at lower operating pressures.

Table 3. Membrane classifications (Bendick, 2003).

Membrane classifications	Size range	Operation pressure (bar)	Rejected particles
Microfiltration	0.01 – 1 μm	0.5-2	Bacteria, Silts, Cysts, Spores
Ultrafiltration	1 nm – 100 nm	1-5	Proteins, Viruses, Endotoxins, Pyrogens
Nanofiltration	200 – 1000 MWCO ⁽¹⁾	3-15	Sugars, Pesticides, Salts
Reverse Osmosis	< 200 MWCO ⁽¹⁾	10-60	Salts

(1) MWCO-Molecular Weight Cut Off.

Four mechanisms for particle rejection are shown in Figure 11. Surface sieving rejects particles by the size of the membrane pores. Surface collection rejects particles by the affinity of the particles to attach to the membrane due to surface charge or other non-specific attractive forces. Surface cake collection influences particles rejection by the formation of a cake that accumulates on the membrane surface and effectively reduces the pore opening of the membrane. Internal pore adsorption occurs when particles adhere to the inside of the membrane pores and are excluded from the permeate. The particles that accumulate on the membrane surface and within the membrane are known as the fouling layer.

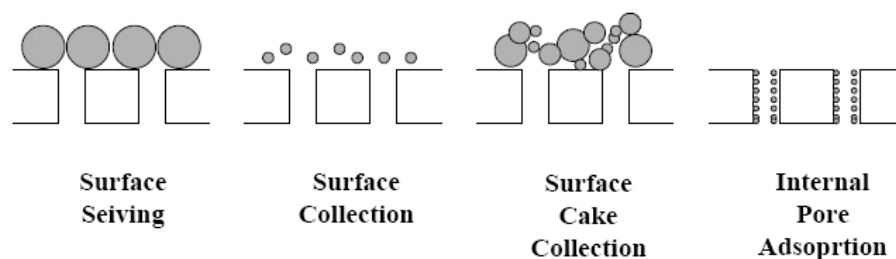


Figure 11. Filtration mechanisms.

(Sources: John A. Bendick, 2003, Feasibility of Cross-flow Microfiltration for Combined Sewer Overflows.)

3.1.1 Materials and Methods

Membrane processes can be further classified by the membrane material and the system configuration. Four basic types of membrane configurations are dead-end, spiral wound, cross-flow, and hollow fiber. The different configurations have been developed to facilitate higher permeate flux rates, process flexibility, and ease of maintenance and operation for specific applications. A dead-end configuration was used in these experiments.

The objective of these tests were to characterize permeate water quality and flux rate that can be achieved for both MWW and AMD blowdown collected from pilot-scale cooling tower test using different types of membranes. Figure 12 shows the schematic diagram of the bench scale dead-end membrane unit employed in these tests. The unit consists of a stainless steel

cylindrical cell that is connected to a feed reservoir. The cell has a holding capacity of 350 mL and an effective filtration area of 36.3 cm². It also incorporates a magnetic stirrer to provide shear force needed to reduce cake buildup on the membrane surface. A sinter metal plate at the cell bottom provides mechanical support for membrane during filtration. Pressurized nitrogen gas from a gas tank can be introduced into the feed reservoir to maintain necessary trans-membrane pressure (TMP). Such pressure drives the feed solution through the membrane. During a batch experiment, permeate is collected in a glass beaker sitting on a top-loading electronic balance. The amount of permeate collected was recorded (accuracy ± 0.01 g) at predetermined time intervals for calculating the flux rates.

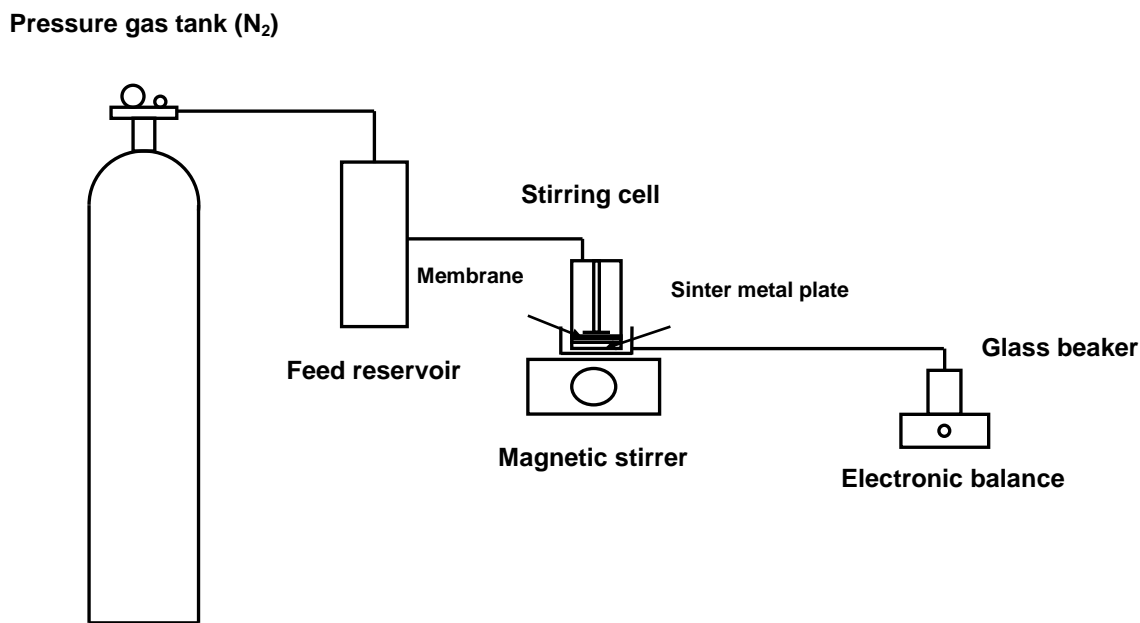


Figure 12. Schematic diagram of the membrane filtration system used for blowdown treatability studies.

For each of the two types of blowdowns tested in this study (AMD and MWW), both synthetic and actual blowdowns were used as feed to obtain additional insight into the performance of different membranes. The synthetic water was designed to simulate the actual blowdown from pilot-scale cooling towers that were operated at four cycles of concentration (CoC 4) with secondary treated municipal wastewater (MWW) and acid mine drainage (AMD). Table 4 and Table 5 provide the chemical compositions of the synthetic MWW and AMD blowdown water, respectively. To be more representative, the chemical recipe developed for synthetic MWW (CoC 4) was based on average values from different MWW reported in the literature, which are not necessarily the same as the chemical composition specific to the Franklin Township MWW used in pilot-scale testing. Nevertheless, membrane filtration performance based on the synthetic water and actual blowdown water collected from pilot-scale cooling towers will be compared in this section. The actually blowdown water was stored in air-tight tanks at 4°C before use.

Table 4. Chemical composition of the MWW blowdown water representing 4 cycles of concentration synthesized for membrane filtration tests.

Cation	Concentration		Anion	Concentration	
	mM	mg/L		mM	mg/L
Ca ²⁺	7.61	305	SO ₄ ²⁻	2.84	273
Mg ²⁺	7.16	174	HCO ₃ ⁻	13.44	820
Na ⁺	13.44	309	Cl ⁻	31.16	1105
K ⁺	0.70	27	PO ₄ ³⁻	0.21	20
NH ₄ ⁺ (as N)	7.14	100			

Table 5. Chemical composition of the AMD blowdown water representing 4 cycles of concentration synthesized for membrane filtration tests.

Cation	Concentration		Anion	Concentration	
	mM	mg/L		mM	mg/L
Ca ²⁺	20.58	825	SO ₄ ²⁻	31.04	2981
Mg ²⁺	10.45	254	HCO ₃ ⁻	4.52	276
Na ⁺	12.51	288	Cl ⁻	8.74	310
K ⁺	0.75	29	SiO ₃ ²⁻	0.78	59

A variety of thin-film composite flat-sheet polymeric membranes were tested in this study. Membrane characteristics in terms of pore size, water affinity, and porosity are shown in Table 6 (data provided by membrane manufacturers).

Table 6. Characteristics of the membranes used in the study.

Membrane		Manufacturer	Material	Water affinity	Pore size (μm)	Clean water flux (gal/m²·min·psi)
MF	AC+0.2	PALL	Acrylic copolymer	Hydrophilic	0.2	7.00
UF	MX500	Filtration Solutions	Modified polyacrylonitrile Polymer	Hydrophilic	0.05	----
NF	NF270	FILMTEC	Polyamide Thin-Film Composite	NF270 > NF90 > BW30	NF270 > NF90 > BW30	0.039
	NF90	FILMTEC	Polyamide Thin-Film Composite			0.020
	BW30	FILMTEC	Polyamide Thin-Film Composite			0.00087
RO	SW30	FILMTEC	Polyamide Thin-Film Composite	BW30 > SW30	BW30 > SW30	0.00016

Based on a review of the federal and state regulations, such as National Pollutant Elimination Discharge System (NPDES), and the water quality of the two blowdowns, it was determined that the following parameters are the critical for the permeate quality: pH, TSS, TDS, sulfate, TOC (only for MWW), nitrate (only for MWW), and phosphate (only for MWW).

The synthetic wastewater was stirred for 24 hours to allow sufficient time for precipitation prior to testing. The actual blowdown water, preserved in a refrigerator (4°C), was well mixed before use. All experiments were conducted at room temperature ($22 \pm 1^\circ\text{C}$) and the entire test system, including water samples, was allowed to equilibrate at room temperature prior to each test.

All membranes were subjected to similar preparation procedure. They were cut into 68mm diameter discs to fit in the dead-end filtration cell and wetted with deionized water prior to use.

Permeate was collected over a period of 6 hours during which time a fixed TMP of 15 psi (for MF), 60 psi (for UF), 135 psi (for NF) or 380 psi (for RO) was maintained (Benitez et al., 2009; Vidic et al., 2005). For MWW blowdown, permeate flux with an NF membrane (model # BW30, DOW) was measured at various pH values (6.0, 7.4, 9.0). The effect of TMP pressure (135, 150 and 200 psi) on the flux rate and permeate quality was also evaluated using NF membrane. In addition to testing single NF membrane, a combined use of two different NF membranes was compared to the results with RO membrane treatment of actual AMD blowdown.

Surface morphology and fouling characteristics of the membrane subjected to different flux conditions was examined after the filtration test. The membrane was carefully removed from

the cell and air-dried before scanning electron microscope (SEM) analysis. The SEM used in this study was a field-emission gun (FEG)-equipped Philips XL30. Images were obtained in the secondary electron (SE) imaging mode. The accelerating voltage and working distance, magnification, scale, etc., were recorded on the images. Samples were coated with Pd metal using a Denton vacuum evaporator to reduce charging during microscopy.

3.1.2 Results and Discussion

3.1.2.1 Repeatability of experimental measurements

To increase the accuracy and reliability experimental results, several measurements of permeate flux and quality were performed in parallel membrane filtration tests.

To test the reproducibility of permeate quality at different times throughout a membrane filtration test with synthetic secondary municipal wastewater (SMWW), the variations of sulfate and phosphate concentration during the first four hours are compared in Figure 13. The data in Figure 13 show small variations in measured concentrations of sulfate and phosphate in the permeate. These variations appear to be random and there was no obvious trend in the results. Furthermore, all variations were within acceptable experimental measurements with a maximum of 8.1% change in sulfate concentration from the average value 128.2 mg/l. Similarly, all phosphate concentrations varied within 4.4% of the mean value. It can be concluded that the

nanofiltration tests in this study achieved steady state performance in terms of permeate quality during the first hour of the filtration experiment and that the experimental techniques used in this study yielded fairly reproducible results.

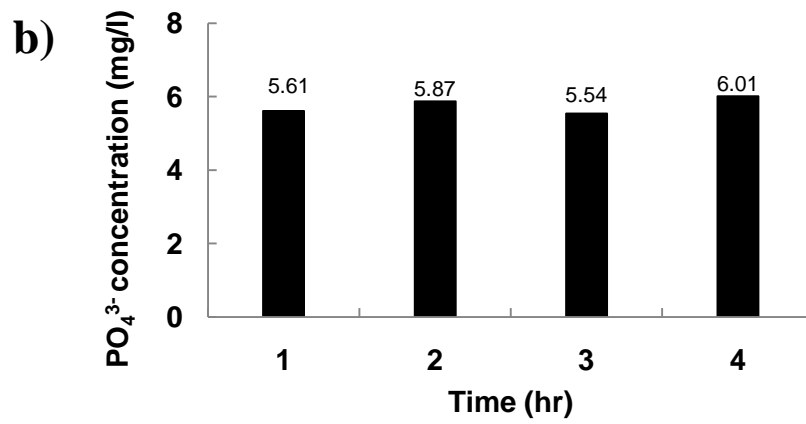
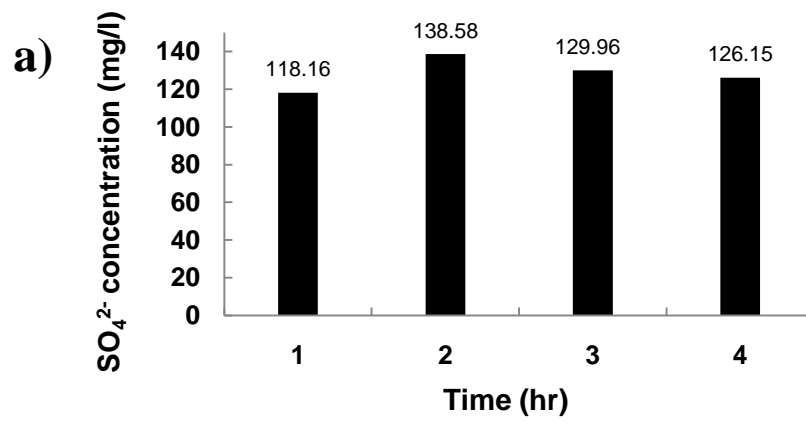


Figure 13. a) Sulfate and b) phosphate concentration variation in SMWW permeate under BW30 membrane with filtering time.

The reproducibility of permeate flux measurements was also performed at the onset of this study using BW30 nanofiltration membrane and synthetic municipal wastewater (SMWW) blowdown. Figure 14 shows the reproducibility of permeate flux measurements in three separate experiments. As can be seen from this figure, the permeate flux in these experiments exhibited fairly consistent and reproducible trend.

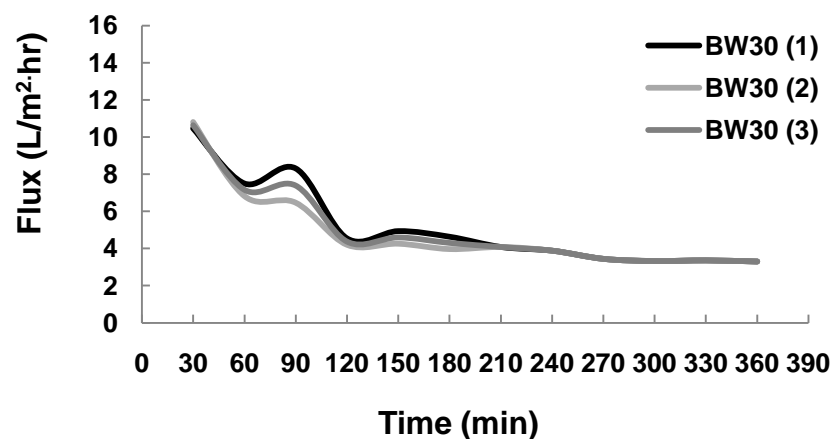


Figure 14. Repeatability of permeate flux with BW30 membrane tested on synthetic MWW blowdown at TMP = 135 psi.

The most significant differences in permeate flux measurements occurred during the first 2 hours of the experiment and all three permeate flux measurements were almost identical after that. It is also important to note that the permeate flux reached steady state values after 5 hours of

filtration (i.e., there was no measurable decline in the permeate flux during the last hour of testing). Figure 15 shows the average flux from these three experiments together with the range of data collected at each time point. It is obvious that there was almost no variation in permeate flux after 210 minutes.

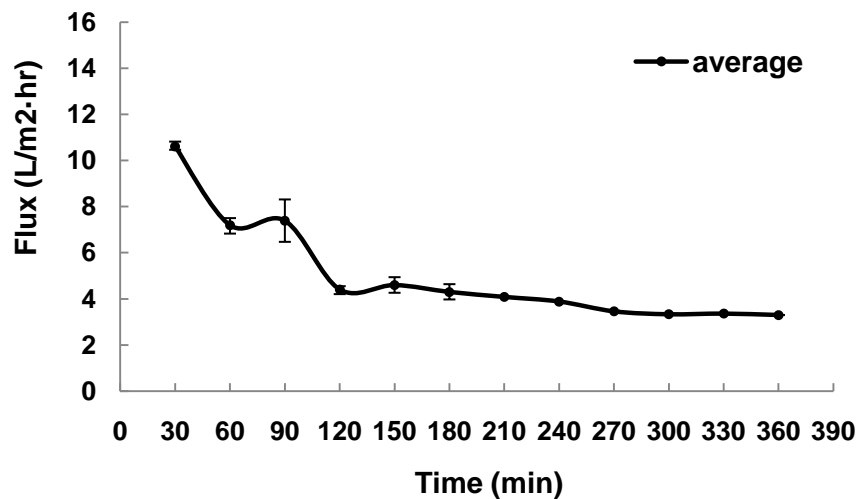


Figure 15. Average permeate flux with confidence interval using BW30 membrane on synthetic MWW blowdown at TMP = 135 psi.

These data suggest that the reproducibility of filtration experiments and measurements is quite satisfactory and that there is no need to conduct multiple experiments under identical experimental conditions. Another important observation from these experiments is that 6 hours

appears to be sufficient time to reach steady-state performance in these laboratory-scale membrane filtration tests. The experimental results shown in the rest of this document represent average values of permeate quality and flux rate obtained from multiple experiments conducted at different times.

3.1.2.2 Filtration of MWW blowdown

Real MWW blowdown from field studies and synthetic MWW blowdown were filtered with five different membranes: MF (AC+0.2), UF (MX500), and three NF membranes (NF90, NF270 and BW30) to determine the feasibility of removing TDS, including specific cations and anions. Sulfate was specifically of interest because it is often high and difficult to treat in impaired waters. The quality of the permeate resulting from the treatment of synthetic MWW blowdown by each membrane is listed in Table 7. The data summarized in Table 7 clearly indicate that MF and UF were unable to remove TDS or the anions of concern. Of the three NF membranes tested, NF90 and BW30 were able to remove some dissolved species from the synthetic MWW. These two membranes were tested with actual MWW blowdown and the permeate quality from these test is summarized in Table 8. These data indicate that the BW30 membrane can be used to treat MWW blowdown to satisfactory levels, yielding permeate quality that meets discharge limits for TDS and sulfate.

Table 7. Permeate quality for synthetic MWW blowdown.

	pH	TSS (mg/l)	TDS (mg/l)	SO ₄ ²⁻ (mg/l)	PO ₄ ³⁻ (mg/l)
Raw water	8.4	17.1	2906	282	12.5
Filtered water					
Membrane:					
MF(AC+0.2)	8.5		2880	280	7.2
UF (MX500)	8.5		2861	282	7.0
NF270	8.3		2794	274	5.5
NF90	8.0		1980	228	5.6
BW30	8.4		1492	130	5.6

Table 8. Permeate quality for actual MWW blowdown filtered with NF membranes.

	pH	TSS (mg/l)	TDS (mg/l)	TOC (mg/l)	SO ₄ ²⁻ (mg/l)	PO ₄ ³⁻ (mg/l)	NO ₃ ⁻ (mg/l)
Raw water	7.8	45	3060	149	282	22	68
Filtered water							
Membrane:							
NF90	7.6		2176	68	326	10	66
BW30	7.1		376	11	31	2	23

In addition to permeate quality, another important aspect of membrane treatment is the permeate flux (volume of permeate produced per unit surface area of the membrane per unit time). Permeate flux needs to be sufficiently high to make this process economically attractive.

A comparison of water flux data from the three NF membranes tested with both synthetic and actual MWW blowdown is shown as Figure 16. For both waters, NF 270 provided the highest water flux. However, the permeate quality using this membrane was not acceptable and it was not evaluated any further. The fluxes from both NF90 and BW30 were very similar when using synthetic MWW blowdown. However, BW30 yielded higher permeate flux and quality with actual MWW blowdown when compared to NF90. In addition, permeate flux with BW30 membrane and actual MWW blowdown leveled off at about $5 \text{ L/m}^2 \cdot \text{h}$ after 6 h of filtration, which indicates fairly robust performance in terms of membrane fouling.

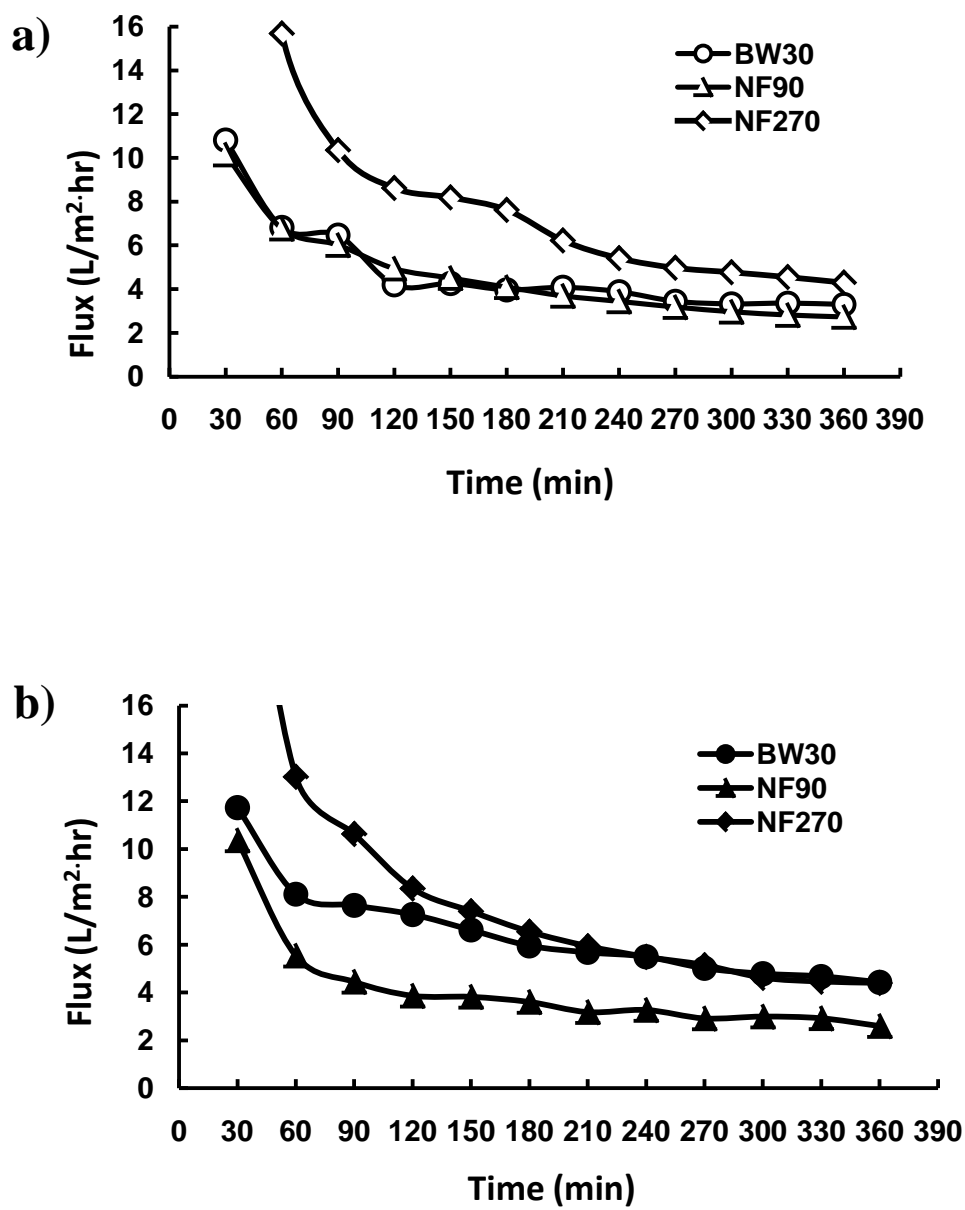


Figure 16. Permeate flux with NF membranes tested on a) synthetic MWW blowdown and b) actual MWW blowdown at TMP = 135 psi.

It is interesting to note that the BW30 membrane yielded higher permeate flux when filtering the actual MWW blowdown than synthetic MWW blowdown (Figure 17). It is postulated that such behavior may be due to the difference in filtering mechanism with two blowdown samples. To test this hypothesis, the membrane surface morphology after the filtration test is compared in Figure 18. A distinctly different “cake” layering was observed for the filtrate on the same membrane from two different water samples. Formation of this layer is attributed to the retention of suspended solids (i.e., organic matter and colloidal particles) originally present in the actual wastewater whereas the synthetic wastewater had lower TSS. It is believed that the more crystalline nature of the thicker cake formed on the BW30 membrane surface operated with the actual wastewater (Figure 18b) can more efficiently intercept particles on the membrane surface and reduce the occurrence of internal fouling than that observed for the membrane that treated synthetic MWW blowdown. In other words, this surface cake layer may have served as a preliminary filter to help mitigate membrane internal fouling to maintain a higher water flux.

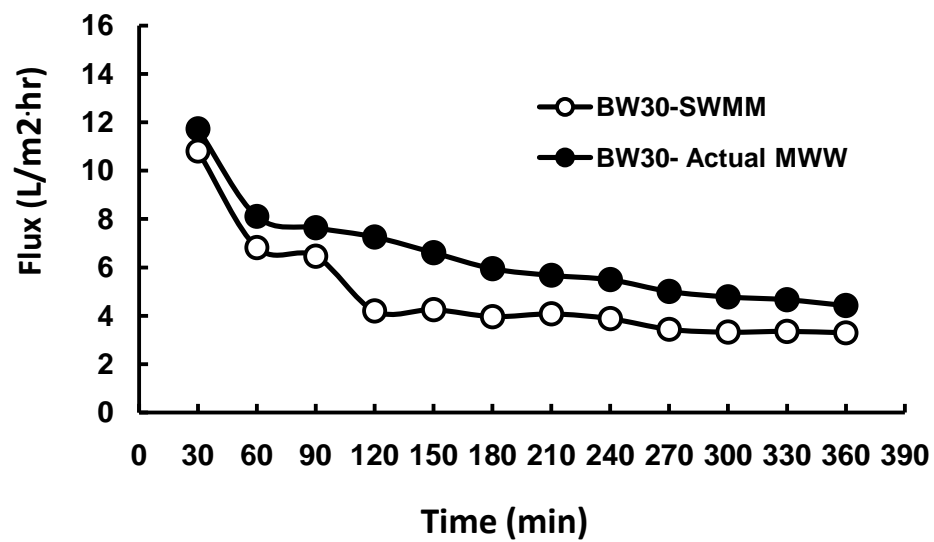


Figure 17. Water flux of the BW30 membrane for synthetic and actual MWW blowdown waters.

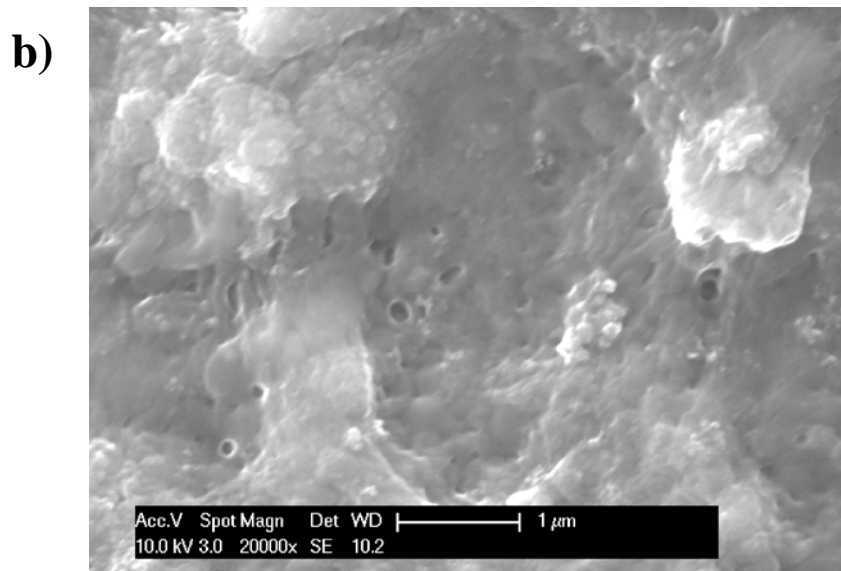
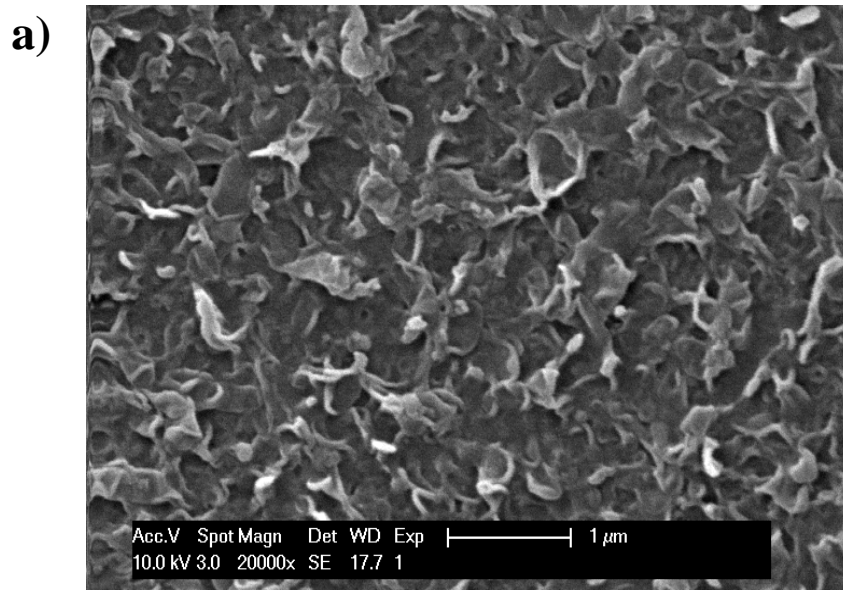


Figure 18. SEM images of the BW30 membrane after filtering (a) synthetic and (b) actual MWW blowdown for 6 h at TMP = 135 psi.

Several TMP values were tested to evaluate its impact on water flux in order to determine optimal operating conditions for BW30 NF membrane in treating actual MWW blowdown. Despite the initial differences in fluxes, there was little difference in steady state flux when TMP values were increased from 135 to 200 psi (Figure 19). This phenomenon may arise from a potential adverse impact of TMP on membrane fouling. For example, an increase in TMP may compress the coating layer (Figure 18b), thereby rendering it less permeable. In addition, higher initial permeate flux at higher TMP may even push some of the layer materials into the membrane pores, thereby increasing the overall filtration resistance of the membrane. Both processes may lead to more severe fouling that would diminish the expected increase in water flux due to an increase in TMP (Figure 20). Therefore, considering the cost of operating membrane filtration at higher TMP, it can be concluded that filtration at TMP above 135 psi cannot be justified.

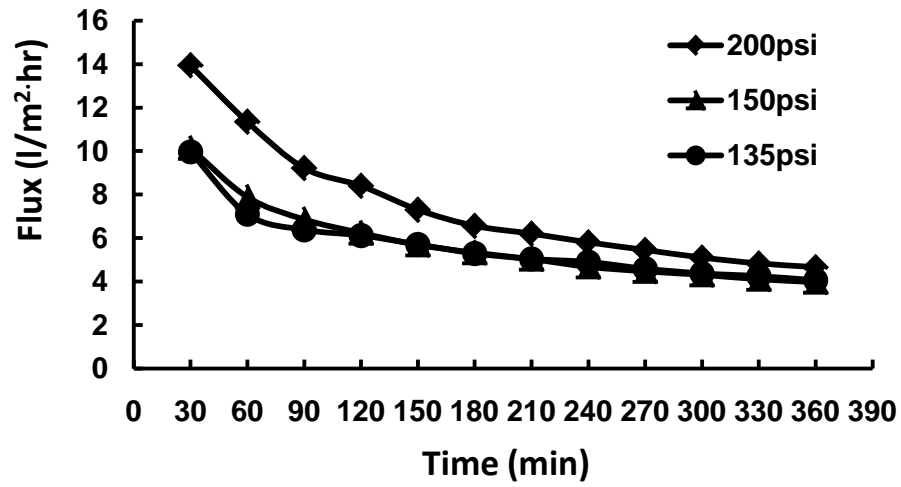


Figure 19. Impact of TMP on water flux of BW30 operated with actual MWW blowdown.

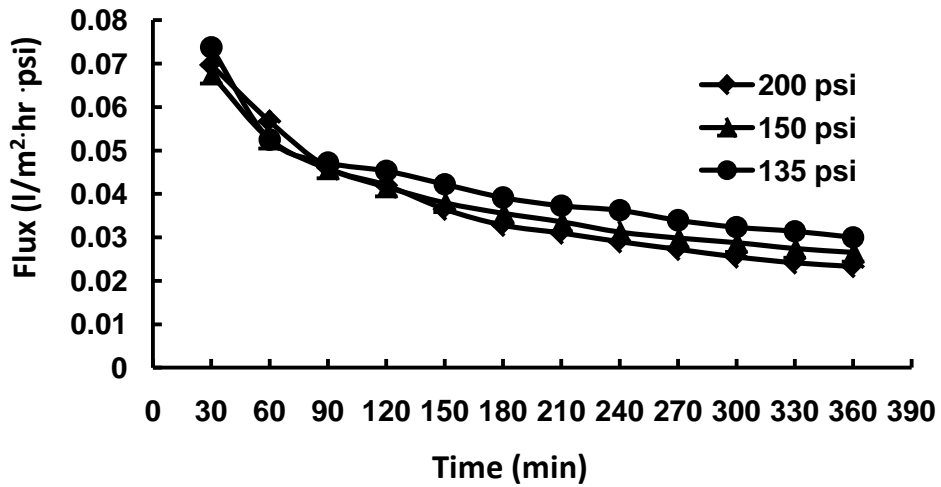


Figure 20. Impact of unit TMP on water flux of BW30 operated with actual MWW blowdown at different pressure.

The impact of pH adjustment on water flux was examined using BW30 operated at 135 psi with actual MWW blowdown (Figure 21). It was observed that lowering pH resulted in higher permeate flux. Elevated pH led to rapid attainment of steady state fluxes at a lower level. It is most likely that higher pH lead to excessive precipitation and severe scaling on the membrane surface (e.g., by CaCO_3 precipitation), which contributed to more pronounced membrane fouling and lower flux. Lower pH waters did not reach steady state within the timeframe of the experiment. So lowering the pH would be beneficial for maintaining higher permeate flux.

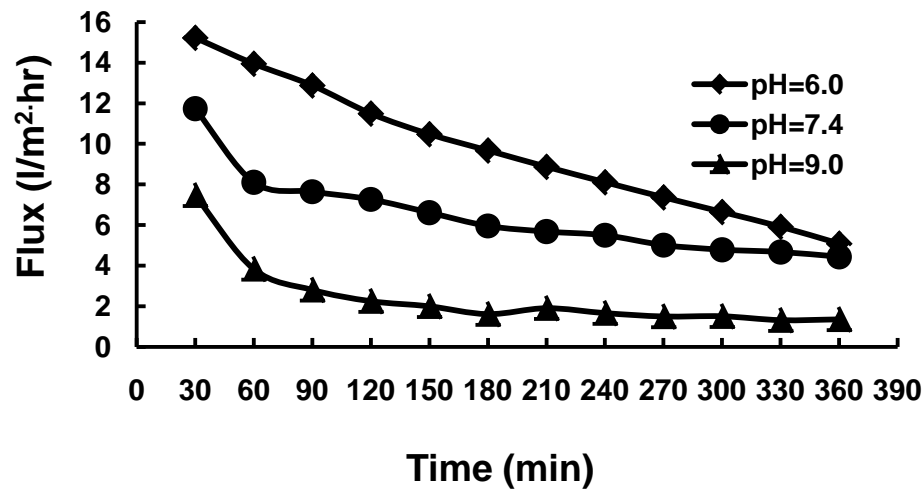
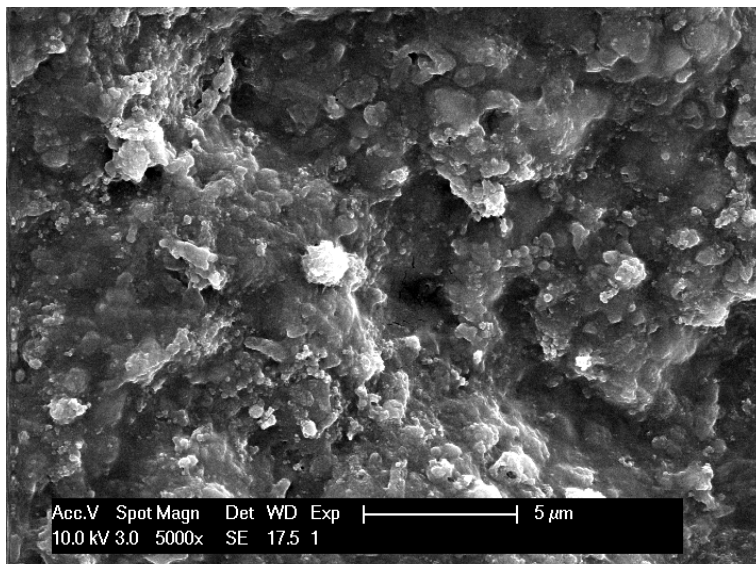


Figure 21. Impact of pH adjustment on permeate flux with BW30 operated with actual MWW blowdown at TMP = 135 psi.

The fouling mechanism was qualitatively investigated by comparing SEM images of membranes used in these tests. The membrane fouling layer resulting from treating blowdown at pH 6 was observed to be more porous and with looser structure than that observed at pH 9 (Figure 22a). The layer at pH 9 was more compact and had a gel-like appearance (Figure 22b). An alternative mechanism that may have contributed to the higher water flux at pH 6 is that the acidic water may partially decompose the fouling layer formed on the membrane surface, thereby having somewhat of a self-cleaning mechanism.

Although lowering the pH of the feed water could bring benefit of higher flux, the cost associated with construction and operation of an acid-base dosing unit should be carefully evaluated before a pH adjustment strategy can be implemented.

a)



b)

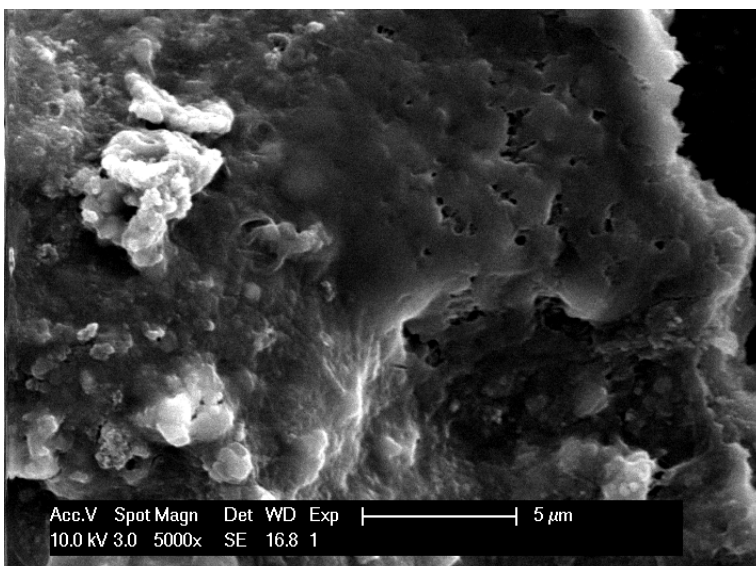


Figure 22. SEM images of the BW30 membrane after filtering the actual MWW blowdown at (a) pH 6 and (b) pH 9.

3.1.2.3 Filtration of AMD Blowdown

Membrane filtration was evaluated as a treatment option for AMD blowdown that would allow its reuse as cooling tower makeup. The performance of membranes tested for TSS and TDS removal from MWW blowdown was considered when selecting the membranes to be tested for AMD blowdown treatment. The three NF membranes, namely NF90, NF270 and BW30, were chosen for this phase of the study that was conducted using the same experimental protocols as those employed for MWW blowdown treatment. The permeate quality that was achieved by these membranes is summarized in Table 9. The data in Table 9 suggest that NF90 and BW30 membranes may be able to control TDS and sulfate levels in the permeate at levels that could allow its reuse as cooling tower makeup water.

Table 9. Permeate quality for synthetic AMD blowdown with different NF membranes.

	pH	TSS (mg/l)	TDS (mg/l)	SO ₄ ²⁻ (mg/l)
Raw water	8.0	22	4815	2495
<u>Membrane:</u>				
NF270	7.9		4129	1889
Filtered water NF90	7.6		1405	690
BW30	7.4		1478	647

Further testing of these two NF membranes was conducted using the actual AMD blowdown and the permeate quality achieved in these test is summarized in Table 10. Results with actual AMD mirrored the synthetic AMD: NF90 and BW30 were observed to improve the quality of blowdown but neither membrane produced permeate that meets the regulatory limits for surface discharge.

Further processing of the AMD blowdown is necessary in order to meet the discharge limits for TDS and sulfate. Two options were tested to further reduce TDS and sulfate in the permeate of AMD blowdown: the sequential use of NF90 and BW30 filters (use BW30 to filter the permeate of NF90), as well as a RO-membrane SW30. The reverse osmosis membrane SW30 was operated at 380 psi and had no additional pretreatment. The results of the sequential NF90-BW30 treatment and SW30 reverse osmosis filtration are shown in Table 11. Both approaches decreased TDS and sulfate to the levels that meet typical NPDES discharge requirements. While both treatment options meet regulatory limits, there are tradeoffs. The RO membrane can produce the required permeate quality but operates at much higher pressure and lower recovery than a combination of two NF membranes. The sequential NF90-BW30 treatment offers better permeate quality but it needs two membrane modules. The choice between the two approaches requires detail process and cost-benefit analysis.

Table 10. Permeate quality for actual AMD blowdown.

		pH	TSS (mg/l)	TDS (mg/l)	SO₄²⁻ (mg/l)
Raw water		8.3	5.6	5810	3079
	<u>Membrane:</u>				
Filtered water	NF90	7.1		761	285
	BW30	7.5		999	420

Table 11. Permeate quality for actual AMD blowdown filtered through two NF membranes in series or single RO membrane.

		pH	TSS (mg/l)	TDS (mg/l)	SO₄²⁻ (mg/l)
Raw water		8.3	5.6	5810	3079
	<u>Membrane:</u>				
Filtered water	NF90-BW30	7.0		192	107
	SW30	7.2		255	138

Variations in the chemical composition of the feed stream can sharply affect the treatment efficiency of nanofiltration membranes operated under identical conditions. The high TDS measured in AMD and MWW blowdown waters as well as high sulfate concentration in AMD water are the main concern for blowdown treatment. The TDS and sulfate removal efficiencies for MWW and AMD blowdown using NF90 and BW30 membranes are shown in Table 12 and Table 13, respectively. These bench-scale experiments suggest that nanofiltration with BW30 membrane is an effective treatment method to reduce concentration of dissolved

species, including sulfate and TDS in MWW blowdown, whereas the NF90 membrane has a small advantage in treating AMD blowdown water. Therefore it is important to pair the membranes filtration technology to the water characteristics in order to achieve the produced water quality goals.

Table 12. Comparison of treatment efficiency of BW30 and NF90 with synthetic MWW and AMD blowdown.

	TDS		SO ₄ ²⁻	
	NF90	BW30	NF90	BW30
Synthetic MWW	32%	49%	19%	54%
Synthetic AMD	71%	69%	72%	74%

Table 13. Comparison of treatment efficiency of BW30 and NF90 with actual MWW and AMD blowdown.

	TDS		SO ₄ ²⁻	
	NF90	BW30	NF90	BW30
Actual MWW	29%	88%	0%	89%
Actual AMD	87%	83%	91%	86%

In addition to permeate quality, the flux of the permeate is an additional consideration for determining the feasibility of membrane treatment for AMD blowdown. The water flux across

the three membranes tested with synthetic AMD is shown in Figure 23a and actual AMD blowdown wastewater in Figure 23b. For synthetic AMD blowdown, there were negligible differences in permeate flux between these membranes. However, NF90 had a higher flux than BW30 when tested with the actual AMD blowdown. Permeate flux for NF90 membrane for actual AMD blowdown reached a steady rate of about $8 \text{ L/m}^2\cdot\text{h}$ over the 6 h period of testing, indicating a more robust anti-fouling performance than the other two NF membranes. Of the three membranes tested, NF90 had the highest permeate flux as well as the highest single pass water quality.

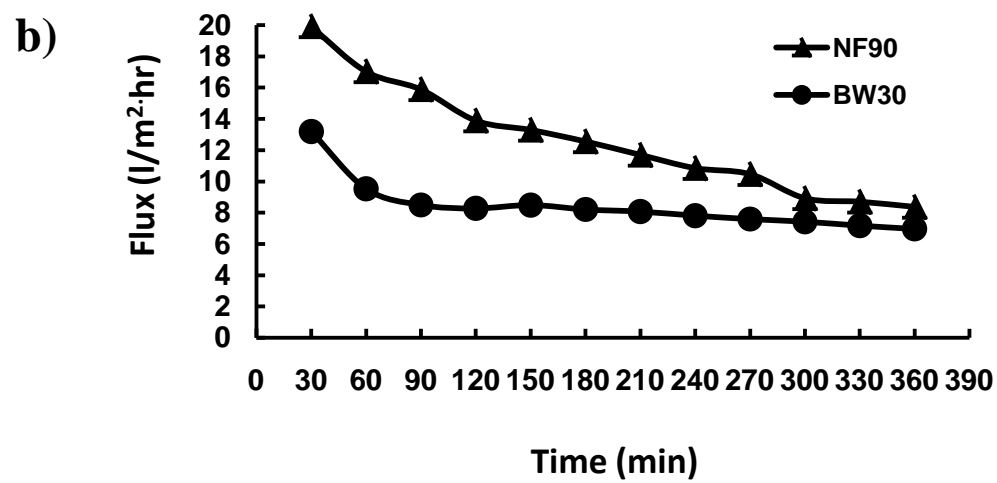
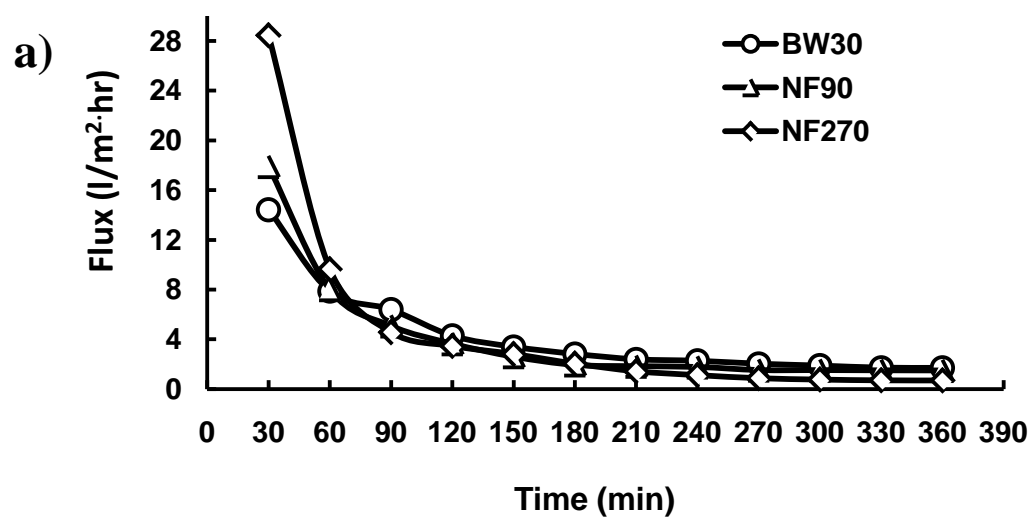


Figure 23. Water flux of NF membranes tested on a) synthetic AMD water and b) actual AMD blowdown (TMP = 135 psi).

Figure 24 shows the permeate flux for SW30 and serial NF90-BW30 membrane filtration for actual AMD blowdown. As can be seen from this figure, the sequential filtration with NF membranes (NF90 followed by BW30) has the higher flux in comparison to filtration with RO membrane (SW30). In addition, the NF90-BW30 combination produced permeated with higher quality. Both configuration tested have shown high permeate flux compared to results with single NF membranes (Figure 23b). Given these results, it was determined that the sequential nanofiltration membrane combination NF90-BW30 is the most effective method to treat AMD blowdown.

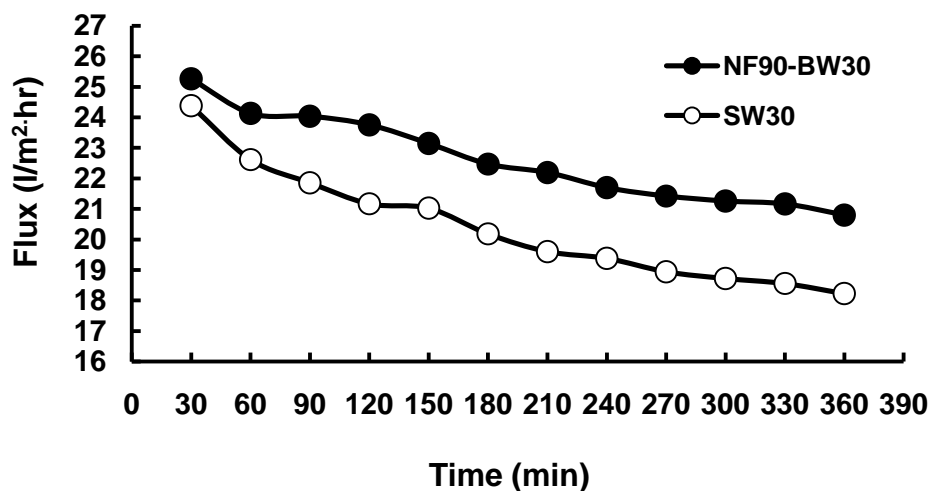


Figure 24. Water flux of actual AMD blowdown for RO and sequential NF filtration.

3.2 OPUS TECHNOLOGY

N.A. Water Systems developed an Optimized Pretreatment and Unique Separation (OPUS) process for desalination of feed water with high concentrations of silica, organics, hardness, boron and particulates that can be used to treat MWW and AMD blowdown. It consists of multiple treatment steps ending with reverse osmosis filtration at a pH near 10.7. A process diagram for OPUS technology is shown on Figure 25. The pretreatment processes ahead of the RO are designed to reduce the hardness, metals and suspended solids in the feed water. This technology generates high quality water with a low waste volume.

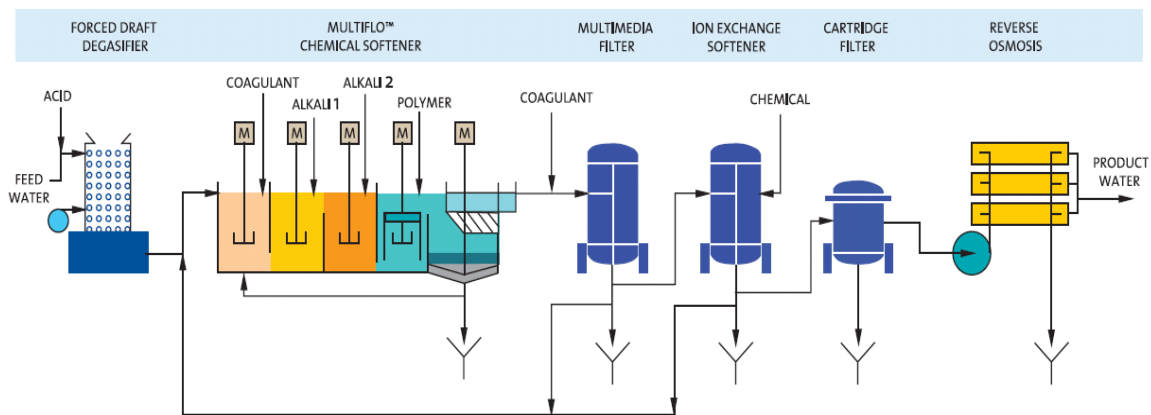


Figure 25. Processes diagram of OPUS technology developed by N.A. Water Systems, a Veolia Water Solutions & Technologies company.

In the OPUS technology, the RO unit for blowdown treatment consists of three stages and each stage separately has 22, 8 and 4 pressure vessels which all include 7 elements each, as shown in Figure 26. Table 14 and Table 15 display the specifications of the systems designed for MWW and AMD blowdown treatment, respectively. Modeling studies regarding the use of OPUS technology to treat MWW and AMD blowdown conducted by NA Water Systems indicate that OPUS technology would be able to meet performance specifications for removing chloride, sulfate, TDS, and other ions as necessary to meet NPDES or relevant discharge regulations. Compared to the nanofiltration membranes tested in laboratory studies, the most important benefit of OPUS technology is the high water recovery rate of 92%. Additionally the elevated pH 10.7 that is used in the finishing RO process effectively controls biological, organic and particulate fouling, eliminates scaling due to silica, and increases the rejection of silica and boron.

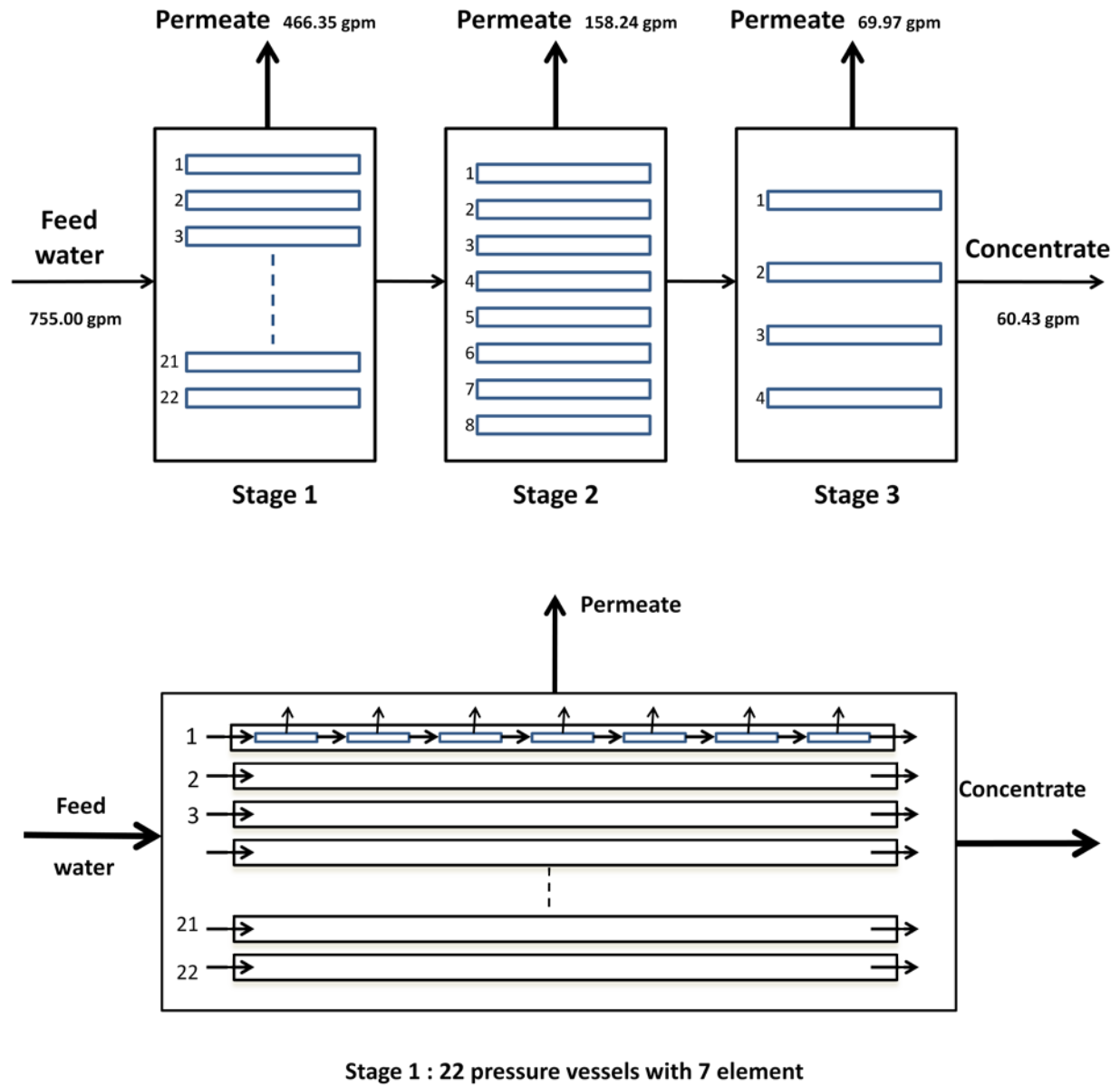


Figure 26. Schematic of RO process in OPUS technology.

Table 14. OPUS system details for MWW blowdown.

Stage	Element	#PV	#Ele	Feed Flow (gpm)	Feed Press (psi)	Conc. Flow (gpm)	Conc. Press (psi)	Perm. Flow (gpm)	Perm. Press (psi)	Avg. Flux (gfd)	Perm. TDS (mg/l)
1	EXPSW370/34i	22	7	754.96	49.05	91.58	39.82	63.38	0.00	1.71	29.19
2	EXPSW370/34i	8	7	291.54	14.82	31.42	04.16	60.16	0.00	1.13	71.30
3	EXPSW370/34i	4	7	131.42	49.16	0.36	40.25	1.07	0.00	0.88	173.92

Pass Streams (mg/l as Ion)

Name	Feed	Adjusted Feed	Concentrate			Permeate			
			Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Total
NH ₄	2.40	2.40	5.50	10.97	21.28	0.45	1.01	2.22	0.76
K	60.00	60.00	151.58	329.27	700.48	2.37	5.78	13.99	4.34
Na	953.89	1072.34	2763.85	6107.76	13240.55	7.94	19.89	49.61	14.96
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO ₃	15.43	321.36	875.92	1975.36	4310.63	0.71	2.82	10.15	1.84
HCO ₃	356.20	46.79	71.18	115.20	216.90	2.67	5.49	10.30	4.42
NO ₃	70.90	70.90	175.62	375.17	784.04	5.01	11.87	27.90	8.93
CL	1043.75	1043.75	2689.16	5940.76	12873.74	8.36	20.49	52.32	15.76
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄	300.00	300.00	776.06	1720.48	3742.98	0.44	1.08	2.70	0.82
SiO ₂	25.00	25.00	64.21	141.45	305.88	0.33	0.82	2.04	0.62
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO ₂	1.19	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
TDS	2827.56	2951.06	7580.94	16721.86	36198.77	29.19	71.30	173.92	53.80
pH	8.50	10.70	10.66	10.51	10.18	9.93	9.97	10.20	9.90

Permeate Flux reported by ROSA is calculated based on ACTIVE membrane area.

Table 15. OPUS system details for AMD blowdown.

Stage	Element	#PV	#Ele	Feed Flow (gpm)	Feed Press (psi)	Conc Flow (gpm)	Conc Press (psi)	Perm Flow (gpm)	Perm press (psi)	Avg Flux (gfd)	Perm TDS (mg/l)
1	EXPSW370/34i	22	7	755.00	383.30	288.65	374.17	466.35	0.00	11.79	22.09
2	EXPSW370/34i	8	7	288.65	484.17	130.41	473.75	158.24	0.00	11.00	55.42
3	EXPSW370/34i	4	7	130.41	718.75	60.43	709.99	69.97	0.00	9.73	136.65

Pass Streams (mg/l as Ion)

Name	Feed	Adjusted Feed	Concentrate			Permeate			
			Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Total
NH ₄	0.50	0.50	1.15	2.29	4.39	0.10	0.22	0.47	0.16
K	29.00	29.00	75.26	165.45	354.32	0.37	0.94	2.32	0.69
Na	1853.53	2021.80	5276.57	11656.87	25099.54	7.26	18.65	46.73	13.83
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO ₃	81.53	492.53	1334.26	2977.67	6406.35	1.21	4.83	6.91	3.15
HCO ₃	461.30	44.11	60.82	95.07	189.23	3.60	7.31	13.22	5.89
NO ₃	4.90	4.90	12.01	25.16	51.19	0.50	1.18	2.67	0.87
CL	370.60	370.60	964.61	2125.91	4565.24	2.94	7.60	19.11	5.63
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄	2930.00	2930.00	7657.11	16935.83	36513.89	4.16	10.63	26.67	7.90
SiO ₂	59.00	59.00	153.06	336.37	720.06	0.78	2.00	4.99	1.48
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO ₂	0.52	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
TDS	5790.36	5960.96	15541.67	34324.60	73908.52	22.09	55.42	136.65	41.36
pH	8.90	10.70	10.60	10.37	10.40	9.84	10.09	10.32	10.01

Permeate Flux reported by ROSA is calculated based on ACTIVE membrane area.

Potential disadvantage of the OPUS technology is the total cost (i.e., capital and operating costs) of this system. Preliminary calculations indicate that the cost for engineering and procurement of the OPUS equipment necessary for a system that is capable of treating 1MGD of MWW or AMD blowdown is between six and seven million dollars. It is likely that the extensive pretreatment required for the application of RO membranes on MWW and AMD blowdown would make this approach significantly more expensive in comparison to BW30 nanofiltration system for MWW blowdown or a combined NF90-BW30 nanofiltration system for AMD wastewater. It is therefore possible that nanofiltration could represent sufficient treatment to restore water quality of MWW and AMD blowdown to at least the source water levels and allow its reuse in the cooling system as makeup water.

4.0 SUMMARY AND CONCLUSION

Management of cooling tower blowdown is one of the key components of cooling tower operation and requires significant attention due to important economic and environmental implications. Due to fairly low water quality, blowdown is typically subjected to some treatment in order to meet local, state or federal discharge requirements that are governed by the final disposal options. Management or disposal options available for cooling tower blowdown depend mainly on its quality, local discharge regulations and capabilities of treatment processes under consideration. Typical options for power plant blowdown management include:

- Discharge to surface waters. This is the main option for once-through cooling systems that is not feasible for recirculating cooling systems because of the low blowdown quality.

- Discharge to wastewater treatment plants (WWTPs): This is probably the most cost effective management alternative but may not be feasible for many plants since the WWTP may not accept the blowdown without any pre-treatment due to extremely high solids and presence of other chemicals in the blowdown that were added to control corrosion, scaling and biofouling.

- Zero liquid discharge (ZLD): Zero liquid discharge means that blowdown is treated and used internally in power plant. This alternative involves extensive treatment of blowdown to facilitate its reuse combined with some form of volume reduction to minimize or eliminate the need for liquid discharge. Most power plants using reclaimed water for their recirculating cooling systems would choose ZLD as the main blowdown management option.

Compared to other discharge options, ZLD is preferred as it helps to decrease environmental impacts of power generation. ZLD typically includes one or more of the following advanced treatment technologies: (1) Reverse osmosis (RO); (2) Electrodialysis (ED); and 3) Evaporation.

The high TDS observed in both AMD and MWW blowdown and high sulfate concentration in AMD blowdown are the main concern in blowdown disposal. The treatment objectives of cooling tower blowdown is to recover portion of the blowdown that will have the quality equal to or better than the makeup water so that it can be returned to the cooling loop. The treatment needs for the blowdown from the pilot-scale cooling towers operated with secondary treated municipal wastewater (“MWW blowdown”) and acid mine drainage (“AMD blowdown”) were independently assessed in this study. The two types of blowdowns were collected from the cooling towers and analyzed for their chemical characteristics and one treatment alternative, membrane filtration, were analyzed through feasibility studies.

Treatability studies with various types of membranes including MF, UF, NF and RO, were carried out for the MWW and AMD blowdown in a bench-scale membrane filtration unit. A variety of operating parameters, including membrane types, trans-membrane pressure (TMP), and feed water pH, were tested for optimal treatment performance in terms of permeate flux and water quality.

Bench-scale experiments provide evidence that nanofiltration with BW30 membrane is an effective treatment method to reduce concentration of dissolved species, including sulfate and TDS in MWW blowdown: TDS and sulfate decreased from 3,060 and 326 mg/L to 379 and 31 mg/L, respectively. Preliminary studies indicate that maintaining a trans-membrane pressure of 135 psi is capable of providing acceptable permeate flux; increasing TMP to 200 psi did not show significant increases in flux due to potentially adverse impact of increased pressure on membrane fouling. Furthermore, lowering pH of the feed water from 7.4 to 6.0 resulted in a higher permeate flux, while increasing it to 9.0 resulted in lower permeate flux. However, a detail cost benefit analysis of the pH adjustment is required before such approach can be recommended.

Treatment of actual AMD blowdown required sequential filtrations by NF90 and BW30 membranes (NF90-BW30) to decrease the TDS and sulfate from 5,810 and 3,079 mg/L to 192 and 107 mg/L, respectively.

5.0 FUTURE WORK

Based on the results of this study, it can be concluded that it is feasible and effective to utilize nanofiltration (separate or sequential) to treat cooling tower blowdown. However, the long-term performance of such a system and wastewater recovery needs to be demonstrated in order to gain confidence in the proposed approach. Similar to the preliminary design of the OPUS system, a number of elements will have to be used to achieve water recovery above 90%. It will be necessary to conduct pilot-scale testing on several different blowdowns to develop a relationship between permeate flux and water recovery in order to obtain preliminary design data for a full-scale system.

In addition, establishing the relationship between the key operating parameters (e.g., pressure, cross flow velocity) and permeate flux is needed to achieve optimal flux at a minimum cost. Also, studies on preventing or reducing membrane fouling to improve the lifetime and performance of nanofiltration system (e.g., pretreatment needs, cleaning approach and frequency) must be conducted before full-scale implementation of the proposed approach for blowdown treatment.

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